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Resonance measurement of the Lamb shift in hydrogenic sulfur

H. D. Sträter, L. von Gerdtell, A. P. Georgiadis, D. Müller, and P. von Brentano
Institut für Kernphysik, Universität zu Köln, 5000 Köln 41, Federal Republic of Germany

J. C. Sens and A. Pape
Centre de Recherches Nucléaires and Université Louis Pasteur, 67037 Strasbourg-Cedex, France

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Using a high-power dye laser, the $2S_{1/2}$-$2P_{3/2}$ transition [$E=2.895\,50(61)$ eV] was induced in a metastable $^{32}S^{15+}$ beam, leading to a deduced value of the Lamb shift of $104.22(66)\times10^{-3}$ eV or 25.20(16) THz.

Measurements of small level shifts in hydrogen and hydrogenic ions constitute an important test of the predictions of quantum electrodynamics (QED) in the limit of short distances and high field strengths. The QED formalism involves the calculation of energy levels in the form of an expansion in terms of $\alpha(\alpha Z)^{4+n}$, where α is the fine-structure constant, Z the nuclear charge, and $n \geqslant 0$, so that for increasing Z the measurement becomes more sensitive to terms of higher order. The subject including results up to $Z=9$ has been reviewed by Kugel and Murnick.[1] From the theoretical point of view, the two Lamb-shift calculations most used for comparison with experimental results are those by Mohr[2] and Erickson[3] which differ, however, by 1.6% for $Z=16$. This difference in the theoretical predictions, together with the development of powerful dye lasers that render measurements possible in several species around sulfur, make resonant experiments in high-Z elements an elegant and exciting possibility.

We report on an experiment with a tunable dye laser that induced the transition $2S_{1/2}$-$2P_{3/2}$ ($\Delta E \approx 2.6$ eV) in a beam of hydrogenic $^{32}S^{15+}$ ions excited to the metastable $2S_{1/2}$ state (Fig. 1). The resonant transition is followed by a fast x-ray transition to the ground state ($\tau=2.4\times10^{-14}$ s, $E=2.6$ keV). The number of x rays was monitored as a function of the laser wavelength. The centroid of the measured resonance determined the $2S_{1/2}$-$2P_{3/2}$ splitting.

A flashlamp pumped dye laser with a peak power of 0.9 MW for 1 μs was developed in Cologne for this experiment. It was operated with the dye Coumarin 1H, which gives nearly constant output power over the whole tuning range and has a lifetime of about 20 000 pulses. The tuning of the laser was done by an air-spaced Fabry-Perot etalon in the range from 465 to 478 nm, corresponding to about 3 full widths at half maximum of the resonance. The wavelength of the laser was measured with a GCA/McPherson EU 700 monochromator which was calibrated with the blue lines of xenon. The laser was operated in a Faraday cage with double rf shielding that completely eliminated the electronic noise from the flashlamp discharge. A microprocessor which controlled the tilting of the etalon and the firing rate of the laser was placed outside the shielding and communicated with the laser by fiber optics. The stability of the laser-beam characteristics with dye age, laser power, and especially wavelength was carefully investigated to make sure that no distortion of the resonance arose from these effects. All these effects were found to contribute negligibly with respect to the final error.

The experiment was performed at the Strasbourg MP Tandem accelerator using a 130-MeV $^{32}S^{9+}$ beam of about 400 nA. To obtain a beam of metastable S^{15+} ions, the primary sulfur beam was stripped and excited by a 100-μg/cm^2 carbon foil and magnetically charge selected by bending the beam through an angle of 9° (Fig. 2). Thus, the contamination of the beam by ions of the neighboring charge state was completely eliminated. The magnetic field (0.6 T) caused a 20% reduction in intensity of metastable ions by motional quenching.

For the matching of the two beams, an angle near 180° has been chosen for three reasons: (i) The angle can be accurately measured by scanning the two beams with one slit

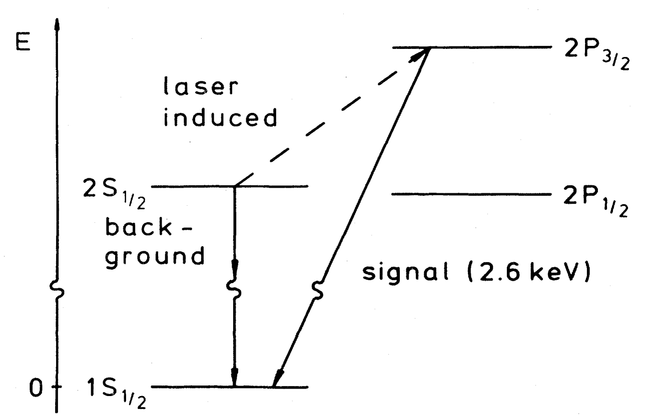

FIG. 1. Partial-energy-level diagram of hydrogenic sulfur.

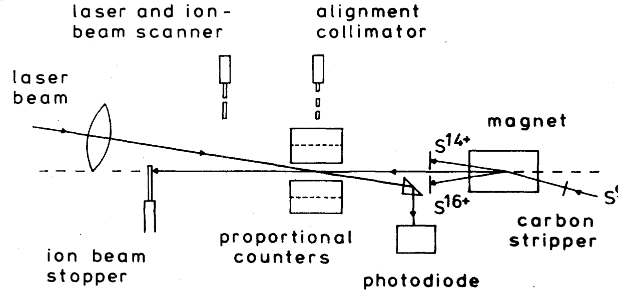

FIG. 2. Schematic diagram of the experimental setup.

$[\theta=177.2(1)°]$. (ii) The Doppler correction is a factor of 20 less sensitive to variations of the intersection angle than in the case of perpendicular intersection. (iii) One obtains a long interaction region (15 mm long, 1.1 mm diam), which raises the count rate by a factor of 10 as opposed to the 90° geometry used by other workers. The 2.6-keV x rays of the $2P_{3/2}$-$1S_{1/2}$ transition were observed by two gas-flow proportional counters which had an energy resolution $\Delta E/E \approx 30\%$ and an overall efficiency of about 10% at 2.6 keV. The efficiency for the background decay ($2E1$ continuum) of the metastable $2S_{1/2}$ state was strongly reduced by a black Supronyl (plastic) absorber foil that also shielded the proportional counters against stray light from the laser.

The experiment consisted in measuring the number of time coincidences between the laser pulse and the 2.6-keV x rays as a function of laser wavelength. Start signals for the time-to-amplitude converter (TAC) were given by the photodiode that monitored the laser power, and the stop signal was given by an event in one of the proportional counters. Signals were processed with standard electronics. A typical time spectrum from the TAC is given in Fig. 3 which shows the resonant events on a background from the natural decay of the $2S_{1/2}$ isomer. The spectrum corresponds to about 4000 laser shots.

The measurement is made up of 22 runs of about 3000 laser shots each. During each run the laser scanned the resonance six times at seven fixed wavelengths. The wavelength was changed every 70 laser shots (1 min) so that the influence of slowly varying parameters was again strongly reduced. The energy of each laser pulse was monitored by a calibrated photodiode to normalize for the dependence on wavelength and age of the dye. The number of metastable S^{15+} ions was measured by counting the nonresonant events for 2 ms, starting 50 μs after each laser pulse.

The velocity of the ions was determined by the analyzing magnet of the accelerator. Its field was measured by a NMR fluxmeter that was calibrated in the Standard procedure using the $^{12}C(p,p)^{12}C$ resonance at $E=14.231$ MeV.[4] Since the fluxmeter probed the field at one position, whereas the energy of the ions is sensitive to the integral field, there might be small deviations from proportionality between the effective and the measured field. The error of the beam energy introduced by this effect was determined to be smaller than 0.12 MeV by a profile measurement of the magnetic field of the analyzing magnet. The energy loss ΔE of the sulfur beam in the carbon foil was accounted for by comparing the energy of the particles with and without foil by a surface-barrier detector three times during the experiment. At 130 MeV an energy loss of $\Delta E=1.87(18)$ MeV was found and a replacement of the foil was not necessary (lifetime $t>60$ h).

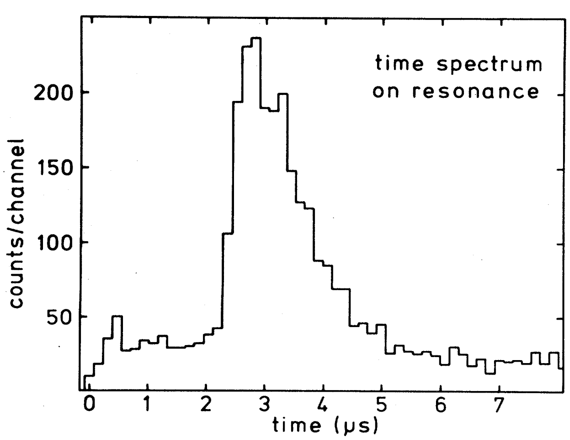

FIG. 3. Number of coincidences between x rays and laser pulses plotted vs the time delay between the two events.

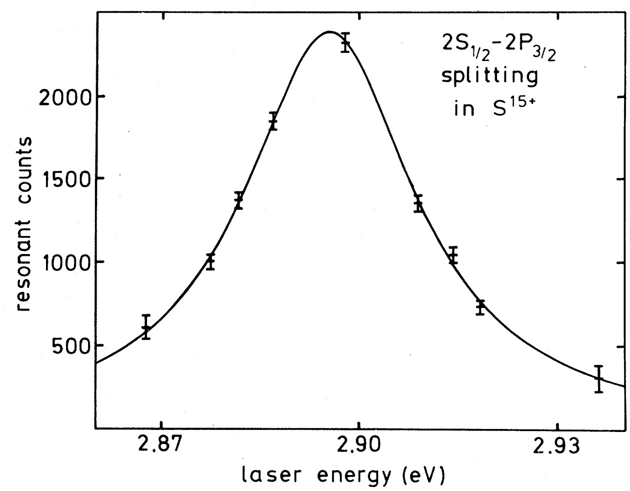

FIG. 4. Resonance curve for the induced $2S_{1/2}$-$2P_{3/2}$ transition in $^{32}S^{15+}$.

Figure 4 gives a plot of the normalized resonant counts together with their statistical error. Each plotted point corresponds to the mean value of approximately 20 points of slightly different wavelengths too close to each other to be shown separately. The fitted resonance curve is a modified Lorentzian[1] (width, height, and center as free parameters) that takes into account that the metastable ions undergo an exponential decay in the laser field. The χ^2 fit yielded a centroid energy of $E(2S_{1/2}\text{-}2P_{3/2})=2.895\,50(61)$ eV. The uncertainty includes the statistical error of the data (0.4 meV), the uncertainty of the laser wavelength (0.3 meV), and the energy of the sulfur beam (0.3 meV), and much smaller contributions (0.1 meV each) due to errors of calibration of the photodiode, the statistical error of the background and interference effects of the $2P_{1/2}$ and $2P_{3/2}$ states.

TABLE I. Theoretical Lamb-shift energies of hydrogenlike ions in THz calculated by Mohr (Ref. 2) and Erickson (Ref. 3), compared with resonant and quenching experiments.

	P^{14+}	S^{15+}	Cl^{16+}	Ar^{17+}
Erickson	20.550(62)	25.792(91)	31.92(13)	39.03(18)
Mohr	20.254(13)	25.373(17)	31.347(20)	38.250(25)
Expt.	20.18(25)[a]	25.20(16)[b]	31.19(22)[c]	37.89(38)[d]

[a] Reference 6.
[b] Present measurement. A preliminary value of 24.44(72) THz has been communicated (Ref. 7).
[c] Reference 8.
[d] Reference 9.

These errors are combined quadratically although they may include systematic errors. The total resonance width $\Gamma = 0.0279(12)$ eV is in agreement with the natural width of the $2P_{3/2}$ state (0.0269 eV). Subtracting the $2S_{1/2}$-$2P_{3/2}$ energy from the well-known $2P_{1/2}$-$2P_{3/2}$ fine-structure splitting [$E_{fs} = 2.999\,72(5)$ eV], which is calculated using the equations of Refs. 3 and 5, the Lamb shift is found to be $E(2S_{1/2}\text{-}2P_{1/2}) = 0.104\,22(66)$ eV [25.20(16) THz].

In Table I the reported values of the Lamb shift for hydrogenic ions around sulfur obtained by different experimental techniques are compared. The experiments agree within their errors with the Mohr calculations, although they tend toward the lower side of his theoretical values. Our measurement on $^{32}S^{15+}$ is more than three standard deviations lower than the Erickson value.

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