Measurement of the $(1s)(2p_{1/2})\ 2^3P_0$–$(1s)(2p_{1/2})\ 2^3P_1$ Fine-Structure Splitting in Heliumlike Ag^{45+}

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A new method is described which is capable of determining $|\Delta E_{0\text{-}1}|$, the absolute value of the fine-structure splitting of the interval 2^3P_0-2^3P_1 from the hyperfine-quenched lifetime of the 2^3P_0 state of heliumlike ions with nuclear spin. Based on this method a measurement is reported of $|\Delta E_{0\text{-}1}|$ in the heliumlike ion $^{107}Ag^{45+}$ with the result $|\Delta E_{0\text{-}1}| = 0.74^{+0.16}_{-0.19}$ eV. The error in the measurement is substantially smaller than the natural linewidth of 1.1 eV.

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The fine-structure splittings of the $(1s)(2p_{1/2})\ 2^3P_J$ states[1] ($\Delta E_{J\text{-}J'}$) of heliumlike ions are determined by the electron-electron interaction. The measurement of these splittings therefore provides a test of the theory of this interaction in the simplest atomic system where it can be observed. The rigorous starting point for all calculations of these splittings is generally accepted to be the Bethe-Salpeter equation[2] and is based on expansions of the Bethe-Salpeter equation in powers of α, αZ, and Z^{-1}. For the 2^3P_J manifold, extremely precise calculations have been performed[3] at low Z for He and Li^+. Extensions of the calculations to higher Z have been based primarily on the variational method developed by Drake[4] and the multiconfiguration Dirac-Fock (MCDF) method of Desclaux.[5]

Accurate experimental measurements of the splittings ($\Delta E_{J\text{-}J'}$) have been performed in He and Li^+ based on radio-frequency spectroscopy[6] and laser spectroscopy,[7] respectively. The extension of laser spectroscopy to the heliumlike ion F^{7+} was achieved by Myers *et al.*,[8] who measured the interval $\Delta E_{1\text{-}2}$. However, extension of the laser method to much higher Z is experimentally not feasible. At higher Z, the splittings $\Delta E_{1\text{-}2}$ can be inferred from x-ray measurements of the transitions 2^3P_1-1^1S_0 and 2^3P_2-1^1S_0 and by taking the difference. The splittings $\Delta E_{0\text{-}2}$ can be inferred from uv measurements of the transitions 2^3P_0-2^3S_1 and 2^3P_2-2^3S_1 and by taking the difference. At higher Z such measurements are generally limited in accuracy by Doppler effects, the presence of satellite peaks, and other systematic effects so that the experimental error is substantially larger than the natural linewidth associated with the lifetimes of the states. Useful reviews of such indirect determinations are given by Martin[9] and Desesquelles.[10]

In this Letter, a new method is described for measuring directly the absolute value of the fine-structure splitting $|\Delta E_{0\text{-}1}|$. It is based on the measurement of the hyperfine-quenched lifetime of the 2^3P_0 state of heliumlike ions with nuclear spin $I \neq 0$. The method is experimentally feasible for many isotopes throughout the periodic table and is capable in some cases of a precision 10–100 times smaller than the natural width associated with the interval due to the lifetime of the states. As a demonstration, we report here an application to the isotope $^{107}Ag^{45+}$ with the result $|\Delta E_{0\text{-}1}| = 0.74^{+0.16}_{-0.19}$ eV. The error should be amenable to substantial improvement, but is already much smaller than the natural linewidth of 1.1 eV associated with this interval.

Hyperfine quenching of the 2^3P_0 state results from mixing with the 2^3P_1 state by the hyperfine interaction. As the 2^3P_1 and 2^3P_0 levels are nearly degenerate for $Z \approx 46$ and as the other levels are relatively far away, the decay rate of the perturbed 2^3P_0 state to the ground state is obtained with high accuracy[11] by solving

$$\begin{vmatrix} E_0 + i\Gamma_0/2 - \lambda & W_{10} \\ W_{10} & E_1 + W_{11} + i\Gamma_1/2 - \lambda \end{vmatrix} = 0, \qquad (1)$$

where

$$W_{10} = \langle 2^3P_0 | H_{\rm hfs} | 2^3P_1 \rangle, \quad W_{11} = \langle 2^3P_1 | H_{\rm hfs} | 2^3P_1 \rangle,$$

and E_0, Γ_0 (E_1, Γ_1) are the unperturbed energy and radiative widths of the 2^3P_0 (2^3P_1) level and $H_{\rm hfs}$ is the hyperfine Hamiltonian. The real and imaginary parts of λ_0 (λ_1) provide the perturbed energy and lifetime of the 2^3P_0 (2^3P_1) level. A fully relativistic calculation of the hyperfine matrix elements has been made and the parameters Γ_0 and Γ_1 evaluated. Details of these calcula-

TABLE I. Theoretical parameters used to determine $|\Delta E_{0\text{-}1}|$ using Eq. (1) and the measured value of $A(2^3P_0)$.

$\Gamma_0 = 7.65 \times 10^{-7}$ eV
$\Gamma_1 = 1.06$ eV
$W_{10} = -0.012$ eV
$W_{11} = -0.0153$ eV

tions will be published elsewhere.[12] Values for these parameters associated with Ag^{45+} are given in Table I. Using these results with Eq. (1), $|\Delta E_{0\text{-}1}|$ can be determined from the measured 2^3P_0 lifetime.

This experiment was performed using the beam-foil time-of-flight technique on the 18.6-MeV/A ^{107}Ag beam provided by the UNILAC accelerator [Gesellschaft für Schwerionforschung (GSI) Darmstadt m.b.H, Federal Republic of Germany]. The extracted beam from the accelerator was initially passed through a 2.35-mg/cm^2 Be stripping foil. The beam emerging from the foil contained 5% hydrogenlike Ag^{46+} which was selected out from the other charge states by a pair of bending magnets and passed into our beam line. The Ag^{46+} was then passed through a 250-μg/cm^2 carbon capture foil which produced the 2^3P_0 and 2^3S_1 excited states of interest here. Radiation from these excited states is observed downstream of the foil by two Si(Li) detectors mounted on opposite sides of the beam (see Fig. 1). One of the detectors is fixed and is used for normalization purposes. The second detector is movable and the time-of-flight data are obtained by measuring the ratio of counts in the movable detector relative to the counts in the fixed detector as a function of position of the movable detector. With this arrangement we normalize directly to the ion population in the excited state of interest. Moreover, changes in the shape or state of the exciting foil during the experiment will not produce any errors in the measurement of the lifetime.

The measurement of the beam velocity was performed with the 10-m time-of-flight spectrometer mounted downstream of the stripping foil. The measured beam velocity was $=0.1915(1)$ and includes, therefore, the correction for energy loss in the stripping foil. The beam velocity was monitored several times during the run and was observed to remain stable. A semiempirical correction was made for the beam velocity in the capture foil, with the result $=0.1910(2)$.

A sample spectrum obtained with the fixed detector is shown in Fig. 2. The large peak is composed of unresolved counts from the $M1$ transition $2^3S_1 \rightarrow 1^1S_0$ and the $2^3P_0 \rightarrow 1^1S_0$ hyperfine-quenched transition. The large peak also exhibits a small high-energy shoulder arising from counts due to the cascade-fed transitions $2^3P_2 \rightarrow 1^1S_0$ and $2^1P_1 \rightarrow 1^1S_0$. A double-humped peak arising at energies around 4.10 keV is also in evidence and is due to $n=3 \rightarrow n=2$ transitions resulting from cascades down the yrast chain.

For each position of the movable detector, the line of interest was treated in the following way. A Gaussian fitting program is used to deconvolute the line into two peaks. In this way, unwanted counts from the high-energy shoulder were removed. The remaining line consists of counts from the hyperfine-quenched $2^3P_0 \rightarrow 1^1S_0$ transition and the $M1$ transition $2^3S_1 \rightarrow 1^1S_0$, plus background counts. The counts in the remaining line were now normalized to the counts in the fixed detector and the ratio plotted versus position of the movable detector to obtain a decay curve. Various ways of fitting the resulting decay curve were tried. The most successful fit used two exponentials plus a constant background. The results of this fit are shown in the decay curve in Fig. 3. A least-squares fit to the data was also performed with a single exponential plus a constant background. It is reasonable to reject the single-exponential plus background fit in favor of the two-exponential plus background fit on at least two counts: (1) The errors on the data points which give a reduced $\chi^2=1.00$ for the two-exponential fit give a reduced $\chi^2=2.53$ for the single-exponential fit corresponding to a probability of 1.0410×10^{-5}. Hence on statistical grounds the two-exponential fit is preferred. (2) The lifetime of the decay $2^3S_1 \rightarrow 1^1S_0$ obtained from the two-exponential fit is $1.14(2) \times 10^{-11}$ sec, in agreement with the theoretical lifetime of 1.11710×10^{-11} sec. The lifetime of the $M1$ decay obtained from the single-exponential fit is 1.06(2)

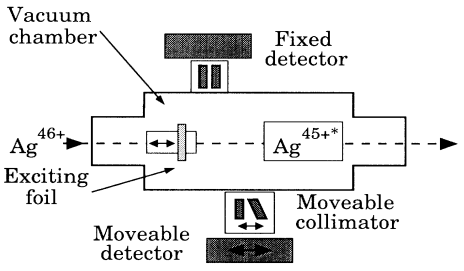

FIG. 1. Schematic of the experimental setup.

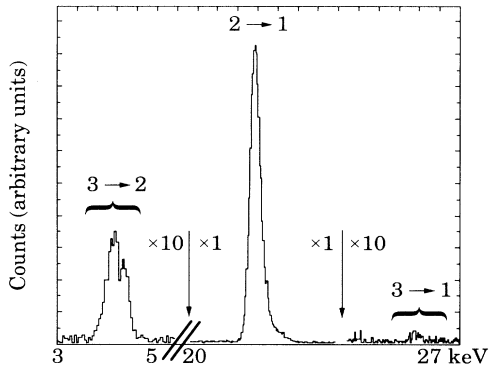

FIG. 2. Sample spectrum showing all the lines observed.

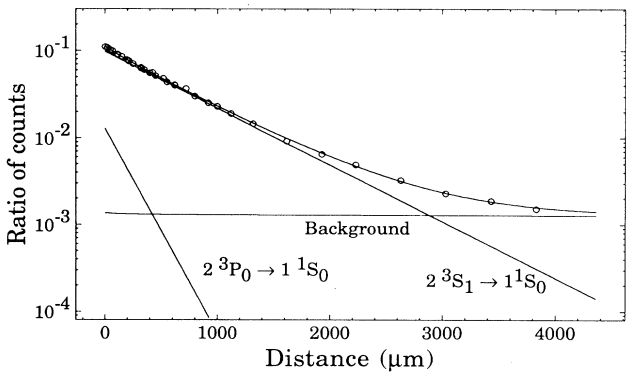

FIG. 3. Decay curve showing the various contributions to the total fit.

$\times 10^{-12}$ sec which is almost 3 standard deviations from the theoretical value. Recent measurements[13] of the $M1$ lifetime in Kr^{34+} and Xe^{52+} are in agreement with theory. There is therefore no reason to expect a departure in Ag^{45+}. On this basis also the two-exponential fit is preferred. From the two-exponential fit we obtain values of 207 ± 62 and 666 ± 15 μm for the decay lengths of the 2^3P_0 and 2^3S_1 states, respectively. Using the measured beam velocity we obtain $\tau(2^3P_0) = (3.551 \pm 1.06) \times 10^{-12}$ sec and $\tau(2^3S_1) = 1.14(2) \times 10^{-11}$ sec for the hyperfine-quenched lifetime and the $M1$ lifetime where these results include a correction for relativistic time dilation. From the value for $\tau(2^3P_0)$ and using Eq. (1) with the values given in Table I we determine that $|\Delta E_{0\text{-}1}| = 0.74^{+0.16}_{-0.19}$ eV.

The experimental errors represent 1σ and are determined almost completely by the statistical error associated with the fit. Systematic errors associated with the experiment arise mainly from uncertainty in the beam velocity, fluctuations in the beam position during the experiment, and possible cascade corrections. These are all determined to be less than 0.5%. The error associated with the theory used to determine the fine-structure splitting from the measured lifetime arises mainly from the estimated accuracy of Γ_1. The other theoretical parameters entering the calculation, Γ_0, W_0, and W_1, either have very little influence on the result or are calculable to high precision. The value of Γ_1 is determined from the MCDF code of Desclaux. Values using this method are in agreement with the variational calculations of Drake[14] and relativistic random-phase approximation calculations of Johnson and Lin[15] at the 0.1% level. Hence the error introduced in our value for $|\Delta E_{0\text{-}1}|$ due to uncertainties in the theory is believed to be less than 0.1%.

A theoretical value of $|\Delta E_{0\text{-}1}| = 0.753$ eV has been calculated based on the MCDF method[16] and also Drake[4] has reported a value of $|\Delta E_{0\text{-}1}| = 0.933$ eV based on variational methods. The experimental result of $|\Delta E_{0\text{-}1}| = 0.74^{+0.16}_{-0.19}$ eV is in good agreement with the MCDF value and in fair agreement with the variational value. Further experiments should lead to substantial improvement in the error.

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[1]In this paper we use as a matter of convenience the L-S coupling notation 2^3P_1 to denote the state $(1s_{1/2})(2p_{1/2})$ $J=1$. Strictly speaking, the actual state in Ag^{45+} is much closer to the j-j coupling limit than it is to the L-S limit.

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