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Lifetime of the $2\,^3S_1$ state of heliumlike $^{79}Br^{33+}$

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We report a measurement of the lifetime of the $2\,^3S_1$ level in heliumlike $^{79}Br^{33+}$. Our result is $\tau^{exp}(2\,^3S_1) = 224.1(7.1)$ ps. This agrees with the theoretical calculation of 230(2) ps and provides a test of $O(Z^2\alpha^2)$ corrections to the lifetime. The experimental error is dominated by uncertainties in the correction required to account for long-lived cascades from highly excited states.

In the past few years, precision measurements of forbidden lifetimes in one- and two-electron ions have been extended to higher Z. The new measurements[1-3] are providing sensitive tests of relativistic quantum mechanics. An important case is that of the lifetime of the $2\,^3S_1$ level in heliumlike ions. This level decays to the $1\,^1S_0$ ground state by a forbidden $M1$ transition.[4] The lifetime of this level is 7.86×10^3 s for the helium atom[5] but decreases as Z^{-10} in heliumlike ions so that for bromine ($Z=35$) the theoretical lifetime is 230 ps. The first observations of the $2\,^3S_1 \rightarrow 1\,^1S_0$ transition were made from satellites and rockets studying the x-ray spectrum of the solar corona.[6] The first laboratory observation was made in a beam-foil measurement by Marrus and Schmieder.[7] Since then the lifetime has been measured[8] over a range extending from $Z=2$–54. Marrus *et al.*[2] have recently reported a 3% measurement in Xe^{52+} which is the first to be sensitive to the $O(Z^2\alpha^2)$ relativistic corrections.

Here we report a 3% measurement of the lifetime of the $2\,^3S_1$ level in heliumlike $^{79}Br^{33+}$. Bromine-79 is a particularly good choice for the measurement of the lifetime of the heliumlike $2\,^3S_1$ level because, in this isotope, all of the other $n=2$ levels which decay by single-photon emission are much shorter lived and so there is a minimum of complication from the decay of other levels. A major factor contributing to this favorable situation is that the lifetimes of the $^3P_0$ and the $^3P_2$ states are reduced by hyperfine quenching induced by the magnetic moment of the ^{79}Br ($I=\frac{3}{2}$) nucleus. For example, in the absence of hyperfine quenching the $^3P_0$ level would decay into $2\,^3S_1$ with a lifetime[9] of 1.48 ns and this contribution would complicate the interpretation of the experimental decay curve. Because of hyperfine quenching, however, this state decays to the ground state with a lifetime[10] of 5.6 ps and the branch to $2\,^3S_1$ is only 0.4%. Figure 1 shows the low-lying energy levels and lifetimes of $^{79}Br^{33+}$. The level with lifetime closest to $2\,^3S_1$ is that of the $2\,^1S_0$ state which decays six times faster. This level decays only by emission of two photons and so will not contribute to the single-photon line. The simplification due to hyperfine quenching does not occur in the Xe^{52+} experiment and it makes our measurement significant even though our result is not as sensitive to the $O(Z^2\alpha^2)$ corrections as the Xe result.

Our experiment utilizes the beam-foil time-of-flight technique for lifetime measurements. A beam of 670-MeV bromine ions from the Argonne Tandem Linac (ATLAS) is incident on a 200-μg/cm^2 foil and the heliumlike 33+ charge state is magnetically analyzed and directed to the experimental area. About 13% of the beam emerging from the foil is in the 33+ charge state. The velocity of the beam is measured to 0.1% with a time-of-flight velocity analyzer located after the linac but in front of the 200-μg/cm^2 foil. The measured velocity must be corrected for energy loss in the foils and this correction dominates the uncertainty in the velocity which

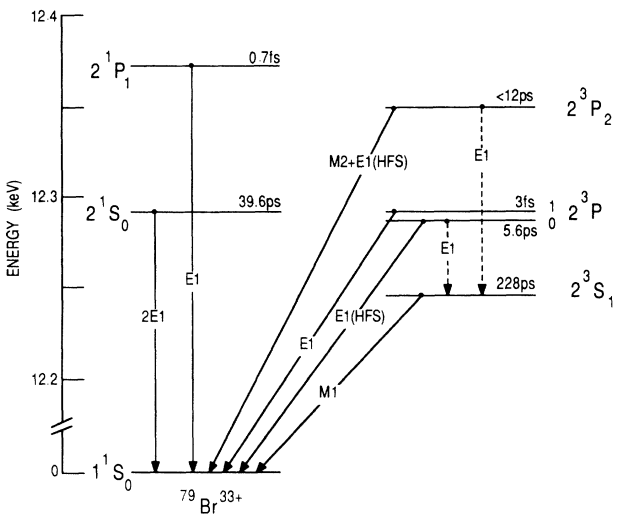

FIG. 1. Electronic energy-level diagram for the low-lying levels of $^{79}Br^{33+}$ showing the decay modes and lifetimes. The $2\,^3P_2$ and $2\,^3P_0$ levels decay primarily to the $1\,^1S_0$ ground state but have small branches to the $2\,^3S_1$ level (dashed lines).

is 0.3%. In the interaction region a thin carbon foil (30 $\mu g/cm^2$) is moved relative to two fixed Si(Li) x-ray detectors by a precision translation stage which measures the position of the target to within 10 μm. The detectors are collimated so that they observe a region 2 mm along the beam. They subtend a solid angle of about 0.05% at the beam. A lower-resolution silicon x-ray detector attached to the target holder observes the x-ray intensity at a fixed foil-detector distance and was used for normalization. The foil-detector distance was varied from 9 to 51 mm corresponding to 1–5.6 lifetimes of the $2\,^3S_1$ level.

A typical spectrum for one of the Si(Li) detectors at a foil-detector separation of 9 mm is shown in Fig. 2. The peak near 12 keV is due to the single-photon decays from the $n=2 \rightarrow n=1$ of heliumlike bromine. Decays from $n>3$ into the $n=2$ levels of two- and three-electron bromine are seen in the energy region above 2 keV. The widths of the peaks are due to the intrinsic energy resolution of the detector (200 eV at 5.9 keV) and the Doppler broadening due to the angular spread in beam velocity and the finite angular acceptance of the detectors.

At each foil-detector separation, the peaks near 12 keV in the Si(Li) detectors and the normalization detector are fitted to a Gaussian with fixed width and position. We then divide the peak areas by the number of counts in the peak of the normalization detector and multiply by the average normalization count. Because we count for the same amount of integrated Faraday cup charge at each foil-detector separation, the normalization corrections are close to unity. The normalized counts are then corrected for pileup and the resulting data for each detector are fitted to a decay curve to obtain the lifetime.

Since higher excited states will be populated in the beam-foil interaction, we need to consider possible systematic effects arising from cascade repopulation of lower-lying levels. Any repopulation of the $2\,^3S_1$ level after our first foil-detector position will give rise to a deviation from a single exponential decay. Also, since we cannot resolve the decays from the $2p$ levels, any cascades which proceed through these states will also lead to a deviation from a single exponential decay.

Repopulation of the $2\,^3S_1$ state will occur via high-lying np levels in transitions $np \rightarrow 2s$. These decays are accompanied by decays $np \rightarrow 1s$ which give counts in our detector above 12 keV. Assuming a statistical distribution among the singlet and triplet states for the np levels, and using known branching ratios for decay of the np levels, we determined the rate of repopulation of the $2\,^3S_1$ level and used this to apply a correction to the data to eliminate the effect of cascade repopulation of $2\,^3S_1$. The correction changes the measured lifetime by less than 0.1%.

Cascade repopulation of the $2p$ levels is a more significant effect in our experiment because of the long lifetimes associated with yrast and high-Rydberg decays. All cascades into $n=2$ will give counts in the region above 2.2 keV ($n=3 \rightarrow n=2$ transition energy), so, in principle, we can determine the intensity of the cascades as a function of foil-detector separation by detecting these lines. Unfortunately the counts near 2.2 keV in our spectra are mainly due to lithiumlike ions and so they cannot be used directly to make corrections for cascades. On the other hand, the population of long-lived Rydberg levels could be similar in the lithiumlike and heliumlike ions and so the dependence of the intensities of the lines near 2.2 keV on foil-detector distance would approximate that of the heliumlike cascades. Our method of correcting for the cascades through the $2p$ levels was then to fit our data to a single exponential plus a constant times the counts in the $n=3 \rightarrow n=2$, $n=4 \rightarrow n=2$, etc. peaks. Some confidence in this procedure is given by the fact that we obtain a slightly better χ^2 probability for the fit using this function as compared to a fit based on a single exponential plus a constant background. We increase the error in our final result to account for the uncertainty in this procedure for handling the cascade correction. Figure 3 shows a typical decay curve obtained by subtracting out the cascade term

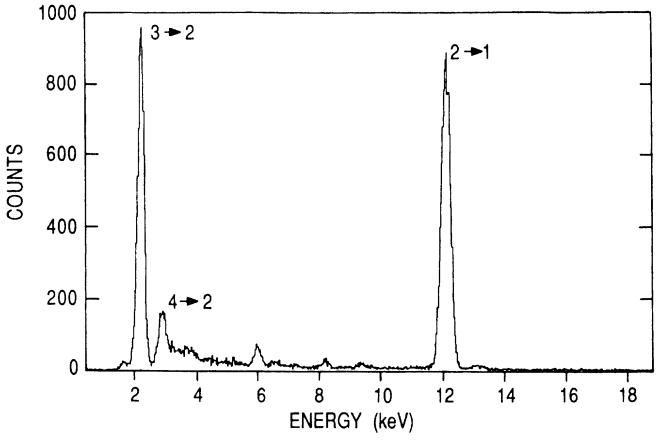

FIG. 2. Typical Si(Li) detector spectrum at a foil-detector separation of 9 mm. The counting time was 12 min and the accumulated Faraday cup charge was 0.9 μC. The peak near 12 keV is mostly due to decay of the $2\,^3S_1$ level of heliumlike bromine. The peaks in the region 2–4 keV are caused by transitions from higher n levels into the $n=2$ levels of heliumlike and lithiumlike bromine.

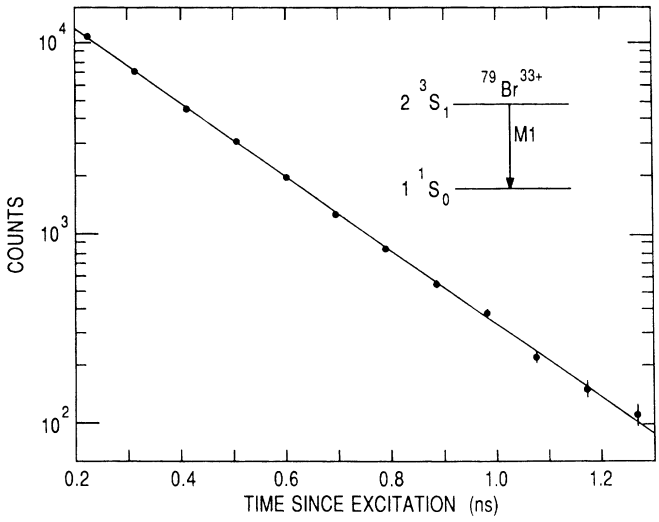

FIG. 3. Decay curve showing data after subtraction of cascade component. The solid line is a fit to a single exponential.

as determined by our fit. The results for the two detectors agree to within uncertainties and so we simply average the two results to obtain our final result of $\tau(2\,^3S_1) = 224.1(7.1)$ ps.

A number of authors have calculated lifetimes for the $2\,^3S_1$ levels in heliumlike ions.[5,11–14] The theoretical calculation to lowest order in $Z\alpha$ can be expressed as an effective operator between nonrelativistic wave functions.[5,13] Drake[5] has evaluated the matrix element to obtain the "nonrelativistic" result $\tau^{NR}(2\,^3S_1) = 245.3$ ps for bromine ($Z = 35$). Lowest-order relativistic corrections are included by multiplying the decay rate by the factor[15] $[1 + 1.07(\alpha Z)^2]$ which yields[16] $\tau^{theor}(2\,^3S_1) = 230(2)$ ps. This agrees with the relativistic Dirac-Hartree-Fock result $\tau^{theor}(2\,^3S_1) = 228.2$ ps obtained by Johnson and Lin[14] which partially includes higher-order relativistic effects. Our experimental result is in agreement with these theoretical values and provides confirmation of the $O(Z^2\alpha^2)$ relativistic corrections.

In order to improve the accuracy of this lifetime determination we would need to reduce the error associated with cascades through the $2p$ levels. With sufficient resolution, one could isolate the $2\,^3S_1 \rightarrow 1\,^1S_0$ line from the $2p \rightarrow 1s$ lines. However, this would involve a considerable loss in detection efficiency compared to a Si(Li) detector. Another possibility is to directly observe the cascades by detecting coincidences between the photons emitted in $n = 2 \rightarrow n = 1$ transitions and photons emitted in $n \geq 3 \rightarrow n = 2$ transitions. Such coincidences were observed in experiments which determined the lifetimes of two-photon-emitting states in heliumlike and hydrogenlike nickel.[3]

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[1] R. Marrus, V. San Vicente, P. Charles, J. P. Briand, F. Bosch, D. Liesen, and I. Varga, Phys. Rev. Lett. **56**, 1683 (1986).

[2] R. Marrus, P. Charles, P. Indelicato, L. de Billy, C. Tazi, J. P. Briand, A. Simionovici, D. D. Dietrich, F. Bosch, and D. Liesen, Phys. Rev. A **39**, 3725 (1989).

[3] R. W. Dunford, M. Hass, E. Bakke, H. G. Berry, C. J. Liu, M. L. A. Raphaelian, and L. J. Curtis, Phys. Rev. Lett. **62**, 2809 (1989).

[4] A. H. Gabriel and C. Jordan, Nature (London) **221**, 947 (1969); H. Griem, Astrophys. J. **156**, L103 (1969); **161**, 1155 (1970).

[5] G. W. F. Drake, Phys. Rev. A **3**, 908 (1971); and (private communication).

[6] W. M. Neupert and M. Swartz, Astrophys. J. **160**, L189 (1970); G. A. Doschek, J. F. Meekins, R. W. Kreplin, T. A. Chubb, and H. Friedman, Astrophys. J. **164**, 165 (1971); A. B. C. Walker, Jr. and H. R. Rugge, Astron. Astrophys. **5**, 4 (1970).

[7] R. Marrus and R. W. Schmieder, Phys. Lett. **32A**, 431 (1970).

[8] J. R. Woodworth and H. W. Moos, Phys. Rev. A **12**, 2455 (1975); J. A. Bednar, C. L. Cocke, B. Curnutte, and R. Randall, *ibid.* **11**, 460 (1975); H. Gould and R. Marrus, Bull. Am. Phys. Soc. **21**, 84 (1976); H. Gould, R. Marrus, and R. W. Schmieder, Phys. Rev. Lett. **31**, 504 (1973); H. Gould, R. Marrus, and P. J. Mohr, *ibid.* **33**, 676 (1974); G. Hubricht and E. Trabert, Z. Phys. D **7**, 243 (1987).

[9] The rate $A(2\,^3S_1 - 2\,^3P_0) = 0.674$ ns^{-1} was obtained by log-log isoelectronic interpolation of the rate calculations in C. D. Lin, W. R. Johnson, and A. Dalgarno, Phys. Rev. A **15**, 154 (1977).

[10] The hyperfine quenching portion of the rate $A(\text{hfs}) = 179$ ns^{-1} was obtained using the equations of P. J. Mohr, in *Beam Foil Spectroscopy,* edited by I. A. Sellin and D. J. Pegg (Plenum, New York, 1976), p. 97. We used 2.106 nm for the magnetic moment of ^{79}Br.

[11] See reviews by J. Sucher, At. Phys. **5**, 432 (1977); and R. Marrus and P. J. Mohr, Adv. At. Mol. Phys. **14**, 181 (1978).

[12] S. Feneuille and E. Koenig, C.R. Seances, Acad. Sci. Ser. B **274**, 46 (1972); W. R. Johnson, Phys. Rev. Lett. **29**, 1129 (1972); G. W. F. Drake, Phys. Rev. A **9**, 2799 (1974); D. L. Lin and G. Feinberg, *ibid.* **10**, 1425 (1974); W. R. Johnson and C. D. Lin, *ibid.* **14**, 565 (1976); C. D. Lin, W. R. Johnson, and A. Dalgarno, *ibid.* **15**, 154 (1977).

[13] I. L. Beigman and U. I. Safranova, Zh. Eksp. Teor. Fiz. **60**, 2045 (1971) [Sov. Phys. JETP **33**, 1102 (1971)]; G. Feinberg and J. Sucher, Phys. Rev. Lett. **26**, 681 (1971); G. W. F. Drake, Phys. Rev. A **5**, 1979 (1972).

[14] W. R. Johnson and C. P. Lin, Phys. Rev. A **9**, 1486 (1974).

[15] D. L. Lin, Columbia University Ph.D. dissertation, 1975 (unpublished); see also J. Sucher, Ref. 11.

[16] G. W. F. Drake (private communication).