RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 39, NUMBER 7 APRIL 1, 1989

Lifetime of the 2^3S_1 state of heliumlike xenon (Xe^{52+})

Richard Marrus
Department of Physics, University of California, Berkeley, California 94720

Pierre Charles, Paul Indelicato,* Lucile de Billy, Chakib Tazi, and Jean-Pierre Briand
Laboratoire de Physique Atomique et Nucléaire, Institut du Radium, Université Pierre and Marie Curie, T12, 4 Place Jussieu, 75252 Paris CEDEX 05, France

Alexandre Simionovici and Daniel D. Dietrich
University of California, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

Fritz Bosch and Dieter Liesen
Gesellschaft für Schwerionenforschung mbH, 6100 Darmstadt, Federal Republic of Germany
(Received 12 December 1988)

A precision measurement has been made of the lifetime of the 2^3S_1 state of Xe^{52+} by beam-foil time-of-flight spectroscopy. The result is $\tau(2^3S_1)=2.554(76)\times10^{-12}$ sec, in agreement with theoretical calculations. This measurement provides the most precise test of the theory of relativistic $M1$ decay and is sensitive for the first time to corrections of $O(Z\alpha)^2$ to the leading term.

Relativistic $M1$ decay is a comparatively rare electromagnetic transition occurring between states which satisfy the selection rules $\Delta J=0,\pm1$ with no parity change and $\Delta n\neq0$. In atomic physics such transitions have been observed in emission[1] from the $2s_{1/2}$ state of hydrogenic ions, the 2^3S_1 state of heliumlike ions (from $Z=1$ to 36) and in absorption[2] they have been studied in experiments on atomic parity violation in the cesium and thallium atoms. They have also been observed in emission in high-energy physics as radiative decay of the bound $(c\bar{c})$ system (charmonium).[3]

The relativistic $M1$ transition is so-called because the theoretical rate is zero in a nonrelativistic formulation and a relativistic picture must be used at the outset. The formalism has been worked out by a number of authors[4] and detailed calculations of the rate for heliumlike ions have been made by a variety of techniques in the range up to $Z=92$. Previous experimental work[1] for $Z\leq36$ has verified theory in lowest order at a level of accuracy $\geq5\%$. In this paper we describe a measurement which extends the beam-foil time-of-flight method to much shorter decay lengths than studied heretofore and with improved accuracy over previous work. In this way we are able to test for the first time the $O(Z\alpha)^2$ corrections to the lowest-order calculations and provide the most precise test of the theory to date.

The apparatus is similar to that used in previous experiment[5] and consists of two Si(Li) detectors located on opposite sides of a target chamber through which the beam passes (see Fig. 1). The detectors view decays in flight from excited ions in the beam through two narrow collimators. The field is about 300 μm of beam length as viewed by the detectors through the collimators. The positions of the exciting foil (325-$\mu g/cm^2$ carbon) and one of the collimators are fixed throughout the experiment. The second collimator is moveable and the time-of-flight data is obtained by measuring the count rate in the moveable detector relative to the fixed detector as a function of position of the moveable collimator. Because of the short decay lengths (≈180 μm), it is important to accurately know the change in position of the moveable collimator relative to the fixed collimator. To achieve this, both collimators are decoupled from the detectors. The fixed collimator is bolted directly to the vacuum chamber, and the moveable collimator is bolted to a precision translator which is bolted in turn to the vacuum chamber. The change in position of the moveable collimator is then monitored with a translational gauge with a precision of ≤0.1 μm. The moveable detector is mounted on a separate translation stage from the collimator, and is moved in step with the collimator, so that the identical effective area of the detector is always looking at the beam. In this experiment, the count rate in the fixed detector is used to normalize the counting rate in the moveable detector. Using this technique, we normalize directly to the ion population in the 2^3S_1 excited state. This technique has the benefit that changes in the shape and state of the exciting foil during the experiment do not produce any errors in the measurement of the lifetime.

This experiment was performed with the 3.56-GeV

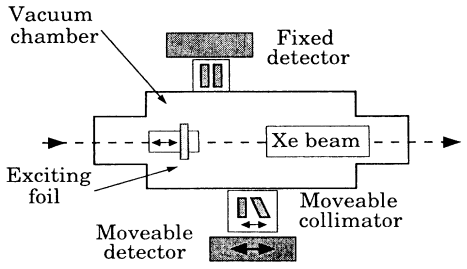

FIG. 1. Schematic of the apparatus.

^{132}Xe beam obtained from the Grand Accélérateur National d'Ions Lourds (GANIL), Caën, France. The full energy beam is passed through a 4.7-mg/cm^2 Be foil used for stripping. This stripping foil is located just before the Ligne d'Ions Super Epluchés (LISE) magnetic spectrometer,[6] and produced approximately 65% Xe^{52+} and 5.1% Xe^{53+}. The LISE spectrometer is set to pass only the hydrogenic Xe^{53+} fraction into our target chamber. The heliumlike ions excited to the 2^3S_1 state are prepared by passing the Xe^{53+} beam through a thin (325 μg/cm^2 carbon) foil (target foil), located just upstream of the detector. The target foil position is set by means of a precision translator, so that the fixed detector does not observe the prompt x rays coming directly from the foil.

An accurate lifetime measurement requires an accurate measurement of the beam velocity and of the decay length. The energy of the beam was established prior to the decay length measurement by passing the full energy beam through the calibrated alpha spectrometer ($\Delta E/E \leq 10^{-4}$). The energy loss (ΔE_S) in the stripping foil was then measured by inserting it in front of the alpha spectrometer ($\Delta E_S = 165$ MeV). The energy loss in the target foil (ΔE_T) was then measured with the LISE spectrometer ($\Delta E_T = 12$ MeV). The final result for the beam velocity is $\beta = 0.23012(8)$. The raw data for determining the decay length consist of spectra taken at different positions of the moveable detector. A sample spectrum taken with the fixed detector is shown in Fig. 2. The large complex peak is composed of counts from the line of interest ($2^3S_1 \rightarrow 1^1S_0$; theoretical energy equals 30123.2 eV), and is also blended with the cascade-fed transition $(1s_{1/2})(2p_{1/2})$ $J=1 \rightarrow 1^1S_0$ (theoretical energy equals 30201.0 eV). The high-energy shoulder of the composite peak arises from counts due to the cascade-fed transitions $(1s_{1/2})(2p_{3/2})$ $J=1,2 \rightarrow 1^1S_0$. The two small peaks observed at higher energies correspond respectively to $n=3 \rightarrow n=1$ and $n \geq 3 \rightarrow n=1$ transitions. The double-humped peak arising at energies around 5 keV is due to $n=3 \rightarrow n=2$ transitions. There is a relatively small background contribution to the line of interest.

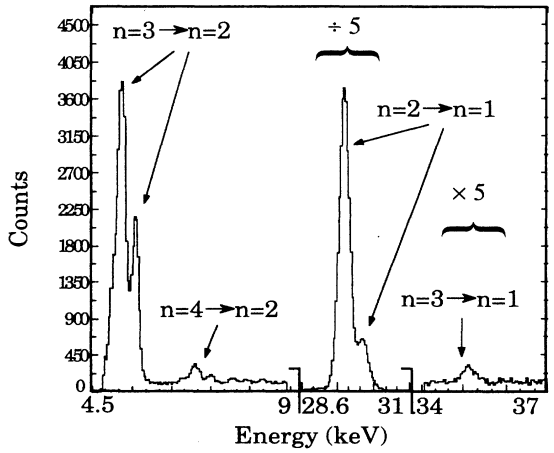

FIG. 2. Sample spectrum showing all the transitions recorded, normalized on the $n=3 \rightarrow n=2$ transitions.

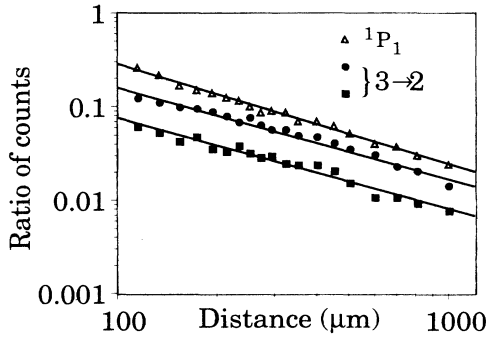

FIG. 3. Power-law decays of the cascade contributions. The solid lines indicate the best fits.

In order to obtain the $2^3S_1 \rightarrow 1^1S_0$ transition free from spurious contributions, the data are treated in the following way. First, the large composite peak is deconvoluted by a Gaussian fitting program with two peaks. The main peak consists of the desired $2^3S_1 \rightarrow 1^1S_0$ counts plus undesired counts arising from three separate cascades contributions: (1) consists of counts resulting from cascades directly into the 2^3S_1 state from electrons in np states with $n \geq 3$; (2) consists of counts resulting from cascades directly into the 2^3S_1 state from electrons originating in the 2^3P_0 metastable state; and (3) a blending contribution, which is the most important, results from the transition $(1s_{1/2})(2p_{1/2})J=1(2^3P_1) \rightarrow 1^1S_0$. The energy of this transition is 78 eV greater than the energy of the $2^3S_1 \rightarrow 1^1S_0$ transition and is unresolved by our detectors. Corrections for the undesired counts are made in the following way. Background counts are subtracted by fitting a straight line through the low- and high-energy sides of the composite peak. Cascade counts from contribution (1) can be accurately determined from the following ar-

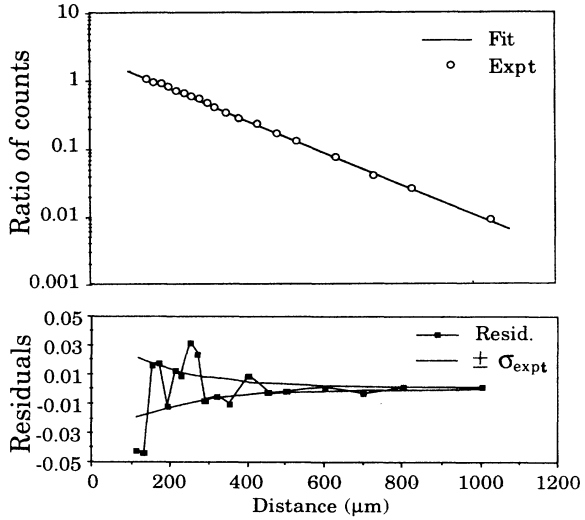

FIG. 4. Sample decay curve; solid line indicates the best fit to the data. The residuals are plotted in comparison with the experimental errors σ_{expt}.

TABLE. I. Theoretical calculations of the lifetime of the 2^3S_1 level.

Calculations	Reference	Lifetime (psec)
Series expansion	8	2.62(2)
GRASP-MCDF	9	2.627
MCDF Coulomb self-consistent	10	2.616
MCDF Coulomb+Breit self-consistent	10	2.631
Series expansion	1	2.646
Series expansion	3	2.636
Experiment		2.554(76)

guments. Ions in the np states with $n \geq 3$ will decay to the ground state ($^1S_0$). These decays are observed in our spectra as peaks at 35.9 keV ($n=3 \rightarrow n=1$) and ≥ 37.8 keV ($n \geq 4 \rightarrow n=1$). From the known branching ratios the number of counts in these peaks provide an upper limit cascade contribution. For all points, the number of such cascade counts is $\leq 1\%$. Cascade contribution (2) arises from the transition $2^3P_0 \rightarrow 2^3S_1$. This transition is very long-lived (theoretical lifetime $= 4.8\times10^{-10}$ sec) compared to the transition of interest. A reasonable estimate of the effect of these cascade counts is made by observing the spectrum looking directly at the foil. This spectrum shows the prompt decay $(1s_{1/2})(2p_{1/2})J=1 \rightarrow 1^1S_0$ which is used to estimate the population of this level at the foil. Assuming the same population for the $J=0$ level, the number of counts arising from 2^3P_0 cascades may be subtracted. The number of counts is $<0.5\%$ of the total rate at the largest foil detector separation. The effect on the lifetime of the correction is 0.08%. A second way to treat this effect is to consider cascade contribution (2) as a small position-independent background present under the main line. We have done such a composite fit to the data corrected for all other effects and find no observable effect on the lifetime.

The blending contribution (3) is the most serious, as its magnitude should be the same as the cascade transitions $(1s_{1/2})(2p_{3/2})J=1,2 \rightarrow 1^1S_0$ observed as a high-energy shoulder to the peak of interest (Fig. 2). The contribution is subtracted by assuming that the number of counts at each point on the decay curve is proportional to the number of counts in the shoulder peak with proportionality constant K, where K is independent of position. The value of K is chosen to give the best statistical fit to the data. Strong evidence to support this procedure comes from the double-humped peak at 5 keV. These peaks arise from the $n=3 \rightarrow n=2$ transitions (fed by the yrast chain) which flow through the $2p$ state of interest here. We have performed a power-law fit to each of these peaks (Fig. 3) and find that the exponent is the same for both peaks, within the fitting error. Using this procedure we obtain for the decay length $\lambda = 181.2(5.4)$ μm corresponding to a lifetime of $\tau = 2.554(76)\times10-12$ sec. The resulting decay curve is shown in Fig. 4 together with a plot of the residuals. The error arises almost entirely from the uncertainty in the cascade correction.

Calculations of the lifetime of the 2^3S_1 state have been performed by a variety of techniques. These techniques include the relativistic-random-phase approximation (RRPA), the multiconfiguration-Dirac-Fock method (MCDF), and series expansion in the parameter $(Z\alpha)$. In terms of the $(Z\alpha)$ expansion, this experiment provides the first result sensitive to the $(Z\alpha)^2$ correction to the lowest-order term. The $(Z\alpha)^2$ correction was worked out by Lin[7] who finds that the leading order term should be multiplied by $[1+1.07(Z\alpha)^2]$. This term contributed 16.6% to the $M1$ rate in the Xe^{52+}. This experiment provides the first test of this term. The results of the available theoretical calculations are presented in Table I.

This work was performed at the Grand Accelerateur National d'Ions Lourds (GANIL), Caën, France under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory, under Contract No. W/7405/ENG-48 and NATO Grant No. RG-252.80. The authors with to express their gratitude to the GANIL staff for their technical expertise in providing the optimal conditions for this experiment. Laboratoire de Physique Atomique et Nucléaire is Unité Associé au Centre National de la Recherche Scientifique No. 771.

*Current address: National Bureau of Standards, Gaithersburg, MD 20899.

[1]R. Marrus and P. J. Mohr, At. Mol. Phys. **41**, 181 (1984).

[2]S. Chu, E. Commins, and R. Conti, Phys. Lett. **60A**, 96 (1977); M. A. Bouchiat and C. C. Bouchiat, Phys. Lett. **48B**, 111 (1974).

[3]J. Sucher, At. Phys. **5**, 432 (1977).

[4]G. Feinberg and J. Sucher, Phys. Rev. Lett. **26**, 681 (1971); G. W. F. Drake, *ibid.* **3**, 908 (1971); W. R. Johnson, Phys. Rev. Lett. **29**, 1129 (1972); I. L. Beigman and U. I. Safranova, Zh. Eksp. Teor. Fiz. **60**, 2045 (1971) [Sov. Phys. JETP **33**, 1102 (1971)]; D. L. Lin and G. Feinberg, Phys. Rev. A **10**, 1425 (1974); G. W. F. Drake, *ibid.* **9**, 2799 (1974).

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

[6]M. Langevin and R. Anne, GANIL Report No. P. 84.16, 1984 (unpublished).

[7]D. L. Lin, Ph.D. dissertation, Columbia University, New York, 1975 (unpublished).

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

[9]I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, and N. C. Pyper, Comput. Phys. Commun. **21**, 207 (1980).

[10]P. Indelicato (unpublished); P. Indelicato, Nucl. Instrum. Methods B **31**, 14 (1988).