Measurement of a magnetic-dipole transition probability in Xe^{32+} using an electron-beam ion trap

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The transition probability for the $3d^4\,{}^5D_2 \leftarrow {}^5D_3$ magnetic-dipole transition in Ti-like Xe (Xe^{32+}) has been measured using an electron-beam ion trap. The unusually weak dependence of the transition energy on nuclear charge Z, and the fact that the transition wavelength remains in the 320- to 400-nm range for $54<Z<92$, makes this transition promising as a plasma diagnostic tool. Our measurement of the transition probability yields 465(30) s^{-1}, corresponding to a lifetime of 2.15(14) ms, in good agreement with the theoretical value of 2.4 ms. [S1050-2947(97)07506-9]

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I. INTRODUCTION

The transition probability between atomic levels is needed in order to determine particle densities from absolute emission or absorption measurements. In plasma diagnostics to avoid the complications of self-absorption, optically thin lines are preferred, that is, regular lines of low transition probability, like spin-forbidden intercombination or electric-dipole-forbidden magnetic-dipole (M1) transitions. It is also preferred that the lines be in the visible or near-uv range of the spectrum, so that high-resolution interferometric techniques can be employed in order to derive a maximum of information, including line shapes and widths.

Such M1 transitions, without faster competing decays, occur in the ground configurations of many ions. These then require relatively low excitation energies and thus are easily excited in plasmas. Many M1 transitions have been observed in Tokamak spectra where their long wavelengths have been used for the determination of quantities, such as ion temperature [1,2]. Unfortunately, however, the wavelength of most M1 transitions varies strongly with the nuclear charge of the ion along a given isoelectronic sequence, as the associated level intervals result from the relativistic fine-structure splitting with its Z^4 scaling in simple systems. This makes the search for, and identification of, such M1 transitions difficult for ions beyond those rather simple cases for which the identification of solar corona lines was possible [3–6]. However, in a lengthy search of computed data Feldman, Indelicato, and Sugar found a particular system in which a single M1 transition had an almost constant wavelength and transition probability over a wide range of nuclear charges [7]. This transition, $3d^4\,{}^5D_2 \leftarrow {}^5D_3$ in Ti-like ions (Fig. 1), was subsequently identified in spectra recorded at the National Institute of Standards and Technology (NIST) electron-beam ion trap (EBIT) facility [8,9] at Gaithersburg. In this work we report a measurement of the associated transition probability, predicted to be about 420 s^{-1} [10] that corresponds to a lifetime of about 2.4 ms. This prediction was obtained with the Cowan code using the scaled parameters for the radial integrals obtained in Ref. [9]. A similar calculation using the multiconfigurational Dirac-Fock GRASP^2 code [11] without any scaling of radial integrals yields 1.97 ms for the lifetime.

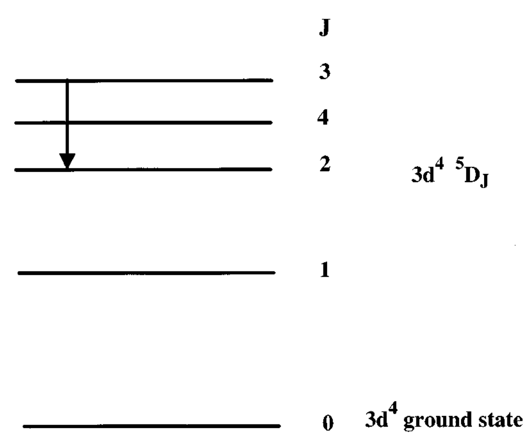

FIG. 1. Lowest levels of a Ti-like ion, indicating the $3d^4\,{}^5D_2 \leftarrow {}^5D_3$ M1 transition of interest at 413.94 nm

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The standard method for lifetime measurements in highly charged ions, beam-foil spectroscopy, does not permit the measurement of such long lifetimes because it would require extremely long flight paths [12]. The technique of slow ion beams [13] needs to be developed further before it can be used for the ms time range. Hence, the present options are the use of an ion storage ring [14–16], ion retrapping from an ion source [17,18], or an EBIT. The last approach was chosen here.

For lifetime measurements using an EBIT, two approaches have been developed. The first relies on trapping highly charged ions by the electric and magnetic fields produced by the electron beam, drift tube potentials, and the superconducting magnet (''electron trapping mode'' [19]). The ion excitation process is modulated for sufficiently separated levels by tuning the electron-beam energy above or below the excitation threshold. Lifetime measurements on the $1s2s\,^3S_1$ level in several He-like ions have been performed at Lawrence Livermore National Laboratory (LLNL) by exploiting this technique [20]. However, this technique does not work for transitions between levels of the ground configuration, because here the level excitation threshold can be insignificant compared to that for production of the ion itself.

A second approach, discussed in Ref. [21], has been developed in parallel at LLNL and at NIST. In this technique, the electron beam current is temporarily switched off so that the ions are confined radially only by the magnetic field, as in a Penning trap, while longitudinal confinement is provided by the drift tube potentials (the EBIT ''magnetic trapping mode'' [22,19]). The LLNL group has done extensive systematic tests on this confinement mode. In particular, they have shown, using an ion-cyclotron resonance probe and x-ray spectroscopy [22–25], that most of the ions remain in the trap immediately after the beam is switched off, but eventually leave the trap with a time constant of greater than 1.5 s. They also confirmed the validity of the lifetime measurement technique on N^{5+} by comparing the result obtained in an EBIT [3.92(13) ms at the one standard deviation level] to the accurate value previously obtained in a storage ring experiment [3.90(5) ms also at the one standard deviation level] [19,14].

II. EXPERIMENTAL SETUP

The EBIT at NIST [26,27] was used as the source of excited highly charged ions in this work. In this source, the desired ion is produced by successive electron-impact ionization from an accelerated electron beam, produced by a electron gun which provides currents up to ~150 mA. A pair of superconducting magnets in a Helmholtz configuration produces an axial magnetic field of 3 T in the trap region and compresses the electron beam to a diameter of ~60 μm, resulting in a current density of ~5000 A/cm^2. Together the electron beam and the magnetic field produce a radial trap for the ions. Axial trapping of the ions along the electron-beam axis is provided by raising the two ends of three collinear, insulated drift tubes to a positive potential with respect to the center drift tube bias potential. This traps a cylindrical ion cloud ~30 mm long and ~200 μm in diameter [28], oriented along the direction of the electron beam. A variable bias voltage of 2 to 20 kV is applied to the drift tubes to define an accelerating potential for the electron beam. A correction on the order of 100 eV must be applied to this energy in order to account for the net space charge of the electrons and the positive ions in the trap. The precise energy of the electron beam (~50 eV width) is therefore determined from the accelerating bias potential, the center drift tube floating voltage and the space-charge correction. By adjusting the accelerating voltage slightly below the ionization energy of the desired ion, we can optimize the relative population of a specific charge state.

A gas injection system connected to a lateral port that looks directly into the trap was used to introduce xenon atoms into the EBIT from a direction perpendicular to the trap. The gas injection system consists of a tunable gas leak, two pump chambers, and three collinear apertures. The apertures are used to define the differential pumping of the chambers and for rough alignment of the gas stream. The first aperture (0.318 cm diameter) is located 67.7 cm from the trap and separates the gas leak from the first chamber. The second aperture (1.27 cm diameter) is located 44.5 cm from the trap and separates the first and second chambers. The last aperture (0.318 cm diameter) is located 32.1 cm from the trap and separates the second chamber and the injection port to the EBIT. The gas leak allows for tuning of the amount of gas injected, which is monitored by an ion gauge located in the chamber between the first and second apertures. Each chamber is pumped by a turbo pump with a pumping speed of about 50 l/s.

The detection system is described in detail elsewhere [8,9]. Briefly, a cooled, low noise photomultiplier was used for photon detection, and a scanning monochromator was used for wavelength selection. Radiation from the trap was imaged onto the entrance slits of the monochromator by two plano-convex lenses; this was necessary to keep the photomultiplier away from the stray magnetic field from the superconducting magnet. The two lens system produced a demagnification of ~0.8. The entire optical table which supported the monochromator was attached to two perpendicular translation stages which could be positioned with a precision better than 10 μm. These translation stages were used to place the monochromator's entrance slit at the image of the trap produced by the lens system. A Si(Li) detector with an energy resolution of ~190 eV, was used to monitor the x rays through one of the radial ports.

III. LIFETIME MEASUREMENT

For the lifetime measurements, we set the drift tube voltage that defines the bulk of the electron-beam energy to 2.172 keV in order to obtain a strong signal from the Ti-like Xe transition. The gas injection pressure of Xe in the first gas injection chamber was changed from run to run. This pressure was varied between 2×10^{-5} Pa (~2×10^{-7} Torr) and 4×10^{-4} Pa (~4×10^{-6} Torr) of Xe, but did not significantly affect the pressure in the EBIT outside of the trap region, which remained lower than ~5×10^{-8} Pa (~5×10^{-10} Torr). A typical electron-beam current for this experiment was about 60 mA. The anode voltage that defines the electron-beam current was driven by a function generator that switched the current off in about 50 μs, kept it at zero

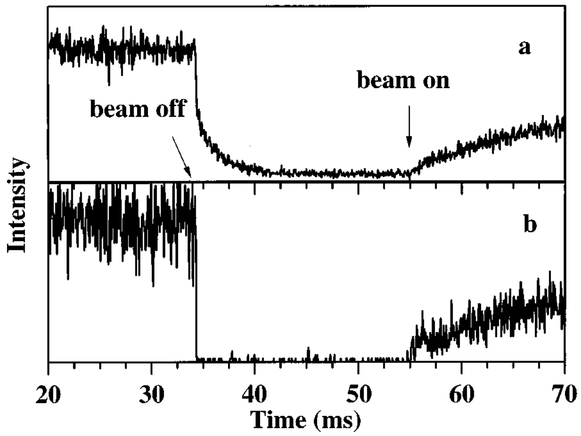

FIG. 2. (a) Time evolution of the visible light signal from Ti-like Xe. The electron-beam current was switched off and on where indicated by the arrows. (b) X-ray time dependence.

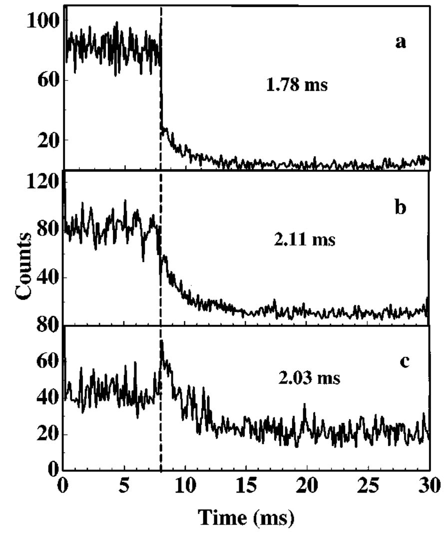

FIG. 3. Time evolution of the visible signal for three different positions of the entrance slit (200 μm wide). (a) Centered on electron beam. Integration time $\sim$ 60 min. (b) Shifted by 200 μm from center. Integration time $\sim$ 108 min. (c) Shifted by 400 μm from center. Integration time $\sim$ 124 min. The dotted line indicates the time at which the electron beam was switched off.

for about 20 ms to allow the transition to decay, and finally switched back on in about 50 μs. The current was then held constant for about 200 ms to allow the signal to recover. Time-resolved data were acquired by setting the monochromator to the transition wavelength and accumulating synchronized data over many thousands of cycles. The entrance and exit slits of the monochromator were set at 500 μm. Photons arriving at the photomultiplier or x rays detected by the Si(Li) detector were time stamped with a resolution better than 50 μs. The timing electronics were constructed from computer automated measurement of control (CAMAC) modules controlled by a list processor interfaced to a computer.

IV. DATA

Data were recorded in both the visible and x-ray spectral ranges. While the visible light, detected in narrow band, offered information on the long-lived level of interest, the x rays, detected in broadband, reflected the total ion population in the trap while the beam was on rather than the charge state and level of interest. For a sample of both the x rays and visible light, see Fig. 2. The short lifetimes associated with the x rays allow us to confirm that the electron beam was switched off rapidly. In an EBIT, a multitude of processes build up to a steady state which yields the extended flat part of our signal curve. When the electron-beam current is suddenly switched off, so is the ion excitation. Consequently, the signal drops, with a time constant corresponding to the lifetime of the observed level. In addition, there may be an initial rapid drop due to ions moving out of the observation region. If all the ion cloud dynamics were reversible in 50 μs, the signal recovery after suddenly switching the electron-beam current back on would be much more rapid than the observations. For extraction of the atomic lifetime, we evaluate only the decay part of the signal curve; we discuss the recovery part of the curve below.

V. DECAY CURVE EVALUATION

The decay curve of the visible signal shows an initial steep fall that extends over about 0.1 ms. We note that this signal loss is over an order of magnitude less than that seen in the LLNL experiments on nitrogen [22,19]. This steep fall can be interpreted either as an actual loss of ions from the trap as the beam is switched off or as a loss of ions from the viewing region of the detection system. The latter would arise from an ion cloud expansion when the electron-beam component of the trapping potential is switched off. Our experimental setup permits access to a viewing region of up to $\sim$ 2 mm in width. The 500-μm slit setting used for most of the measurements restricts the viewing region to $\sim$625 μm. In order to observe the ion cloud expansion and quantify the effect of a restricted viewing region on the lifetimes we narrowed the slits to 200 μm and translated the spectrometer in a direction perpendicular to the viewing axis. Figure 3 shows three sets of data at different entrance slit positions and their repective fitted lifetimes. The expected ion expansion, when the electron beam is switched off, can be seen directly in Fig. 3(c). From the decay constants obtained from the data in these tests and the one from a run with 1-mm slits (2.01 ms), we obtain a standard deviation of 0.14 ms for the decay constant. This uncertainty of about 7% includes the uncertainty due to reproducibility. The final quoted value for the lifetime is the average from five different data sets taken with 500-μm slits centered on the electron beam. The standard deviation from these measurements is also a measurement of the uncertainty due to reproducibility and agrees with the 0.14-ms uncertainty obtained above from the different slit positions.

The data were fitted to a single exponential function plus a background representing the detector dark rate. Successive initial data points were omitted to study the influence of the rapid switching of the electron beam on the data evaluation; after very few points were removed (corresponding to $\sim$ 0.1 ms) the fit results became stable. Figure 4 shows a typical fit to a data set and the corresponding residuals. Similarly the tail of the decay was truncated to find out about a hypothetical slow decay component (perhaps relating to ion loss from

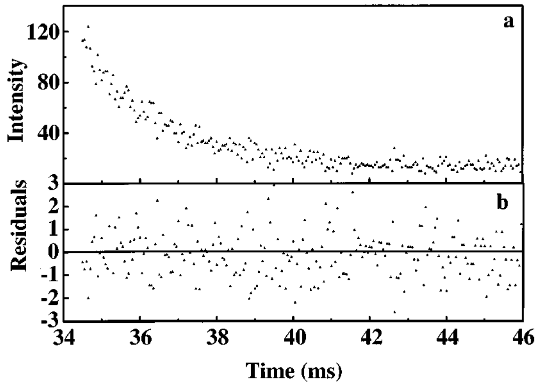

FIG. 4. (a) Fit of one data set to a single exponential plus a constant background (χ_r^2=0.95). Same time scale as Fig. 2. (b) Normalized residuals $(y_{\text{fit}}-y)/\sqrt{y}$.

the trap), but no second decay component could be extracted. By comparing fits from different runs we found no significant dependence for pressures below 4×10^{-4} Pa ($\sim4\times10^{-6}$ Torr) at the gas injection chamber.

An extensive computation was made to assure that the lifetime was not influenced by slow cascading from higher levels. Since E1 transitions are much faster than M1 transitions, we restricted the simulation to configurations that could contribute to slow M1 transitions. Only levels of the $3p^6\,3d^4$ configuration contribute to such transitions, since the levels of $3p^6\,3d^3 4s$ can decay to $3p^6\,3d^4$ through two E1 transitions via the $3p^5\,3d^5$ configuration. The GRASP^2 code [11] was used to calculate the energy levels and transition probabilities among the 34 levels belonging to $3p^6\,3d^4$. We assumed a range of initial populations [equally populated, statistically populated $(2J+1)$, and proportional to J] for the levels and found that the predicted contributions to the lifetime from cascading were smaller than 1%.

Based on the statistics, reproducibility, viewing region, and various truncation exercises discussed above we obtained a lifetime of 2.15(14) ms, at the one standard deviation level. This is considered to be in good agreement with a theoretical value of 2.4 ms [10].

The lack of symmetry of the decay and the recovery part of the signal upon switching the electron-beam current off and on indicates that the ions do not reassemble quickly into the electron beam where they can be reexcited. A variation between 5 and 40 ms of the time interval during which the electron beam is switched off yielded no recognizable differences in this behavior. Apparently the ion cloud needs a few hundred ms to reestablish the steady state. Such an effect suggests that there are irreversible processes at work, which might involve geometry and ion cloud dynamics.

VI. CONCLUSION

The present study completes the quest [7] for, the identification and wavelength measurement [8,9], and now the transition rate measurement of a line particularly suited for plasma diagnostics of future high-temperature tokamaks. As the theoretical expression for the probability of such M1 transitions depends mostly on angular-momentum factors and the transition energy, this dependence has now been corroborated and a suitable benchmark been provided for similar transitions. It needs to be stressed, however, that *ab initio* calculations do not have enough accuracy to predict these fine-structure intervals, and thus the M1 transition energies, with anything close to spectroscopic accuracy.

The magnetic trapping mode of EBIT operation has demonstrated its usefulness for lifetime measurements in the ms range. Improvements that are anticipated for future work include faster electron beam-current switching to measure shorter lifetimes, online diagnostics to monitor the spatial distribution of the ion cloud in the trap, and further investigation and modeling of the ion cloud dynamics and its perturbation by the electron-beam switching.

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