Radiative lifetime of the metastable $^1S_0$ state of Xe^{2+}

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The radiative lifetime of the $^1S_0$ metastable state of Xe^{2+} has been measured with a different type of electrostatic ion trap. The ion trap stores ion beams of a few keV using purely electrostatic fields and provides a large field-free region where the stored ions oscillate. A photomultiplier working in the single-photon counting mode was used to observe the 380 nm photons arising from the magnetic dipole ($M1$) transition $^1S_0 \rightarrow {}^3P_1$ of Xe^{2+}. The present measurement yields a value of 4.46 ± 0.08 ms, which is in good agreement with previous measurements, but is almost four times more accurate.

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I. INTRODUCTION

Measurements of radiative lifetimes of metastable states in ionic systems provide valuable information for understanding the emission lines in astrophysical objects [1], plasma modeling [2], solar physics [3], and also for the testing and advance of atomic and molecular physics theory [4]. Together with branching ratios between the different decay modes, such measurements provide a reliable source for a direct estimate of the transition probabilities [5]. In particular, excited states that have an electronic configuration similar to the ground state are forbidden by parity selection rules to undergo spontaneous decay via an electric dipole ($E1$) transition. Hence such states have transition probabilities many orders of magnitude lower than the dipole-allowed $E1$ transitions.

In the case of Xe^{2+}, the magnetic dipole ($M1$) transition ($^1S_0 \rightarrow {}^3P_1$) represents the dominant decay channel with more than 90% of the total transition probability with a wavelength of 380 nm. A semiempirical calculation by Garstang [6] for the $M1$ and $E2$ ($^1S_0 \rightarrow {}^3P_2$) transition rates using parametric least-square fits to the observed energy levels yielded a mean lifetime value of 4.4 ms. A revised calculation by Hansen and Persson [7] using a similar method to that of Garstang, after a proper reassignment of the $^1S_0$ level, yielded a value for the lifetime of 4.9 ms.

The earliest measurement for the lifetime of the $^1S_0$ metastable state of Xe^{2+} by Johnson [8] was erroneous due to the incorrect assignment of the $^1S_0$ level. One year later, Walch and Knight [9], using a cylindrical radiofrequency ion trap and the proper transition wavelength, measured the lifetime to be 4.5 ± 0.3 ms. A subsequent measurement with the same wavelength by Calamai and Johnson [10], this time with a Kingdon-type ion trap, yielded a value of 4.6 ± 0.3 ms. Table I summarizes the status of theoretical and experimental data for the $^1S_0$ metastable state of Xe^{2+}. Due to the relatively large experimental errors in the previous measurements, there is no way to differentiate between the two theoretical estimates. The main sources of these experimental uncertainties are related to the corrections made for the residual gas pressure in the trap. As the ions are produced in the trap by electron impact ionization from a gas pulse, collision-induced decays have to be taken into account. This correction is the largest source of uncertainties in the final value.

In this paper, we present a method for measuring the lifetime of metastable states with much higher precision. The measured lifetime can be corrected for collisional induced decays without knowing the exact value of the pressure in the trap. Furthermore, as the ion source is external, and the residual gas pressure is very low, this correction is small.

II. EXPERIMENT

In the present experiment, we have measured the lifetime of the $^1S_0$ metastable state of Xe^{2+} using a new type of electrostatic ion trap. Figure 1 shows a schematic diagram of the ion trap and the photon-counting setup used. Since the details of the ion trap and its mode of operation have been published previously [11,12], only a brief description is presented here. Xe^{2+} ions produced in a commercial electron-impact ion source (Colutron Inc.) are extracted and mass/charge selected with a Wien filter and a 20° magnet. The ion beam then enters the trap through a 1 mm aperture. The ion trap consists of two sets of electrodes that act as electrostatic mirrors when suitable voltages are applied. The ion trap is maintained at a pressure $< 2 \times 10^{-10}$ Torr. When trapping, the voltages on the entrance electrodes (see Fig. 1) are switched on (the voltages of the exit electrodes are always on), and the ions oscillate between the electrostatic mirrors. The number of trapped ions decays due to collisions with the residual gas [12]. The beam lifetime is given by

TABLE I. Experimental and theoretical lifetime of the $^1S_0$ metastable state of Xe^{2+}.

Nature of determination	Lifetime value (ms)	Authors
Theory	4.4	Garstang [5]
Theory	4.9	Hansen and Persson [6]
Experiment	4.5 ± 0.3	Walch and Knight [8]
Experiment	4.6 ± 0.3	Calamai and Johnson [9]
Experiment	4.46 ± 0.08	present work

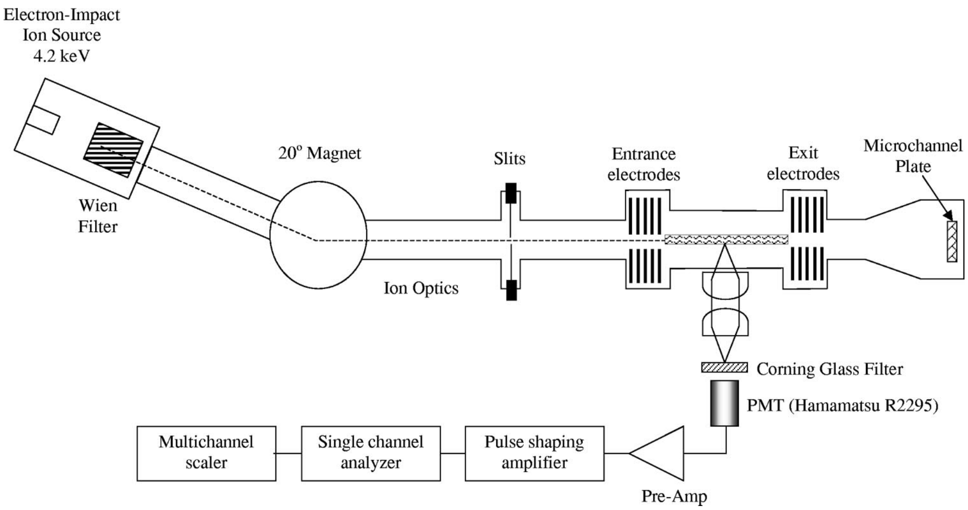

FIG. 1. Schematic of the experimental setup with the photon counting system.

$$\tau = \frac{1}{n\sigma v}, \tag{1}$$

where n is the density of the residual gas molecules present in the trap, σ is the destruction cross section, and v is the velocity of the ions.

The 380 nm photons emitted by the decay of the $^1S_0$ state are detected by a photomultiplier tube (PMT) (Hamamatsu R2295) with a 3 mm diameter photocathode. This PMT was chosen because of its small dark count rate. The acceptance solid angle of the PMT was increased by a pair of sapphire lenses attached to the sapphire viewport of the trap. In front of the PMT was a 380 nm Corning Glass filter with a maximum transmission of about 70% and a bandwidth of 40 nm. This bandwidth was adequate since there are no other transitions near the one under study. The dark noise of the PMT was measured to be about 1 Hz.

The total photon detection efficiency of the setup was estimated by considering the individual transmission efficiencies of the optical elements, the acceptance solid angle of the PMT, and the quantum efficiency of the PMT at 380 nm wavelength. A Monte Carlo simulation performed after taking into account the above mentioned parameters yielded an overall efficiency of the photon detection system to be $\sim 3 \times 10^{-4}$.

The experiment was performed as follows. The Xe^{2+} beam with an unknown composition of the $^1S_0$ metastable state was trapped. Each trapping cycle lasted 50 ms before the trap was refilled. A multichannel scaler was triggered 10 μs after the voltages on the entrance electrostatic mirrors were switched on, and stopped after 50 ms. On an average, about 1.2 photons were counted for each trapping cycle. This is about 20 times larger than the dark noise of the PMT. However, because of the relatively fast decay of the metastable state (see Sec. III), most of the true signal is measured for times below 15 ms. Based on the calculated total efficiency of the photon detection system, it is estimated that a few thousand ions in the $^1S_0$ metastable state were present in each trapping cycle. The beam lifetime [Eq. (1)] was monitored by detecting the neutral and singly charged xenon atoms (produced by charge exchange processes with the residual gas) escaping from the trap with a microchannel plate detector located at the exit side of the ion trap (see Fig. 1).

III. RESULTS AND ANALYSIS

Figure 2 shows the time dependence of the 380-nm photon counts as measured with the system described above. The data could be accurately fitted by a single exponential decay curve plus a time-independent background. It was confirmed after systematic checks with and without the trapped beam that the flat background is purely due to the dark noise of the PMT system. The fitting procedure yields a lifetime of $\tau_{\mathrm{meas}} = 4.452 \pm 0.073$ ms. The stability of the fitting procedure was confirmed by moving the starting bin by a few bins. The exponent was found to be constant within the error limits and the fit converged within a small number of iterations.

The only correction factor to be applied to this value is related to the finite lifetime of the Xe^{2+} beam itself. Figure 3 shows a measurement of the lifetime of the beam, measured by detecting the neutrals and singly charged xenon ions escaping the trap with the microchannel plate detector located downstream (see Fig. 1). A fit with a single exponent plus a time-independent background yields a lifetime for the beam of $\tau_{\mathrm{beam}} = 2.88 \pm 0.015$ s, a value which is much longer than the lifetime of the metastable state. Thus, the correction due to the finite lifetime of the Xe^{2+} beam is very small and the lifetime of the $^1S_0$ metastable state is calculated as

$$\frac{1}{\tau_{\mathrm{meta}}} = \frac{1}{\tau_{\mathrm{meas}}} - \frac{1}{\tau_{\mathrm{beam}}}, \tag{2}$$

where τ_{meta} is the lifetime of the metastable state. Applying this correction yields a final value of the lifetime of $\tau_{\mathrm{meta}} = 4.46 \pm 0.08$ ms for the $^1S_0$ metastable state.

The present result is almost four times more accurate than the previous measurements. While our result is generally in good agreement with other experimental values and Garstang's [6] semiempirical theoretical estimate, it is about 10% lower than the calculations of Hansen and Persson [7] (see Table I). However, it is interesting to point out that the value given by Hansen and Persson [7] is a correction to the

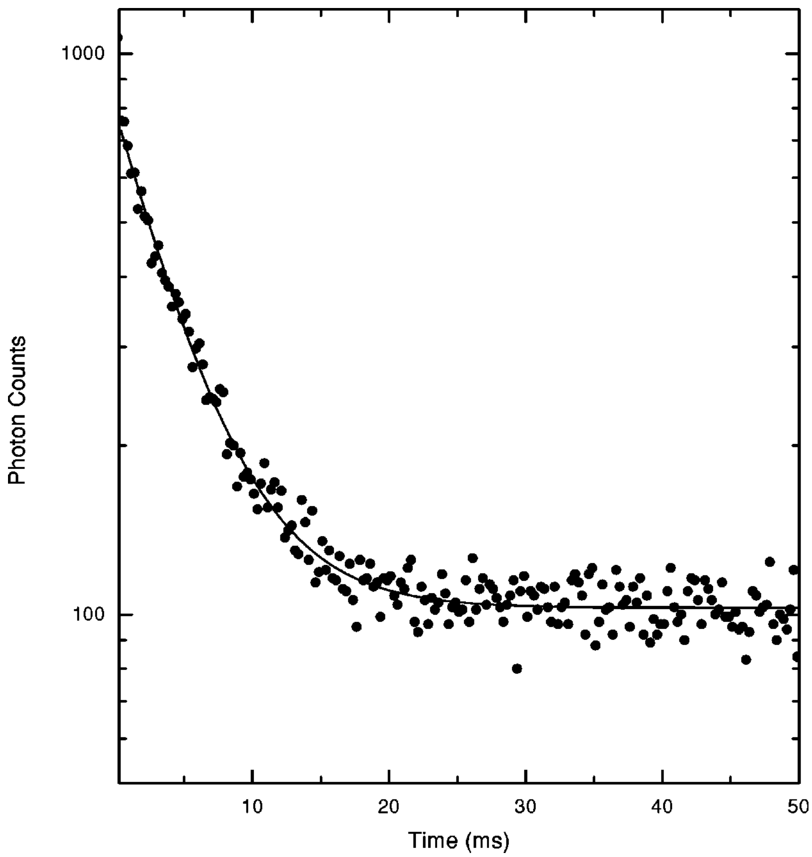

FIG. 2. Photon decay curve. The solid line is the result of a nonlinear least-squares fit to the data.

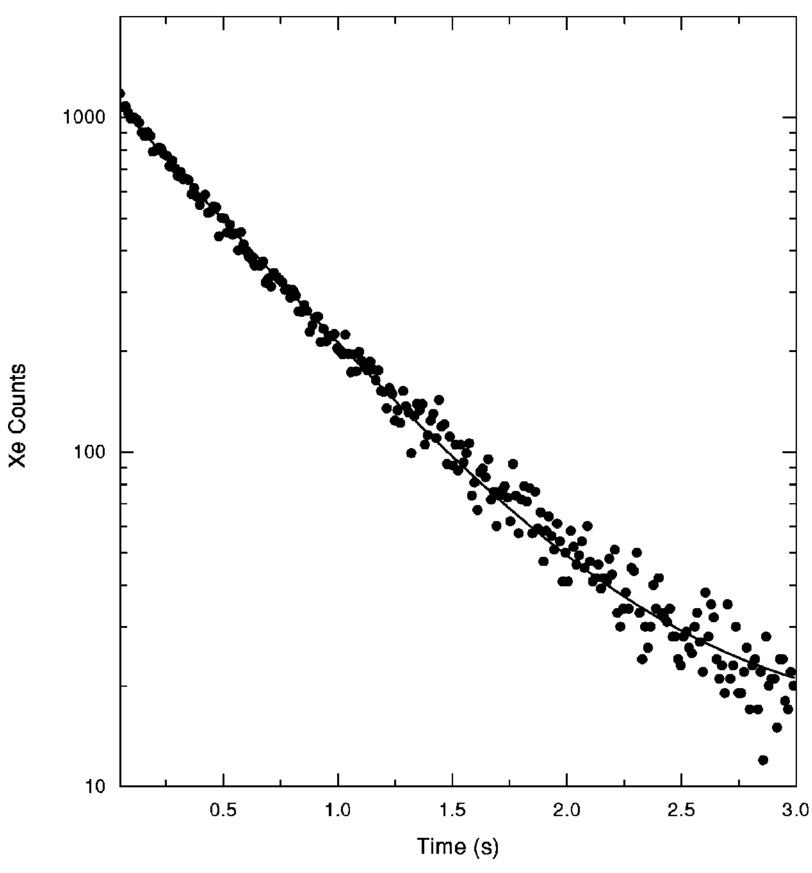

FIG. 3. Neutral and singly charged Xe atoms signal from the microchannel plate detector as a function of time. The solid line is the fit to the data as described in the text.

original lifetime calculated by Garstang [6], as the identification of the $^1S_0$ level in the $5p^4$ ground configuration was in error. Because both theoretical calculations are probably less accurate than the difference between them, the good agreement of our value with the theoretical results of Garstang's [6] can only be considered coincidental. We are hopeful that our results will encourage new calculations using more accurate techniques.

The previous measurements which were conducted with either an RF ion trap [9] or a Kingdon ion trap [10] had larger error bars since the Xe^{2+} ions were created inside the trap. Hence collisional quenching of the metastable states [13] due to higher trap pressure (lifetime had to be extracted by extrapolating to zero trap pressure) and stray light from the electron gun filament added to the uncertainty in the final values for the radiative lifetime. In our measurement, both the external ion injection into the trap and the low background pressure proved to be advantageous. Also, because the light is detected when the ions are in the field-free region, reflectors can be easily added inside the trap to improve collection efficiency.

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