Lifetime of the $2s_{1/2}$ state in hydrogenlike fluorine and oxygen*

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Beam-foil measurements of the lifetimes of the $2s_{1/2}$ states in hydrogenlike fluorine and oxygen have been performed. The experimental results of 237 ± 17 nsec (fluorine) and 453 ± 43 nsec (oxygen) are in good agreement with the respective theoretical values of 228 and 464 nsec. Our results indicate that meaningful beam-foil lifetime measurements can be made on systems whose lifetimes are in the hundreds-of-nanosecond region and whose decay can be followed over only a fraction of a decay length.

INTRODUCTION

Beam-foil measurements of the lifetime of the $2\,^3S_1$ state in heliumlike chlorine, argon, and titanium[1] have recently been reported. This state is expected to decay via a relativistically induced $M1$ transition to the $1\,^1S_0$ state. In the case of titanium, the theoretical lifetime of 27.4 nsec is in adequate agreement with the measured value of 25.8 ± 1.3 nsec, but the theoretical lifetimes in the cases of argon and chlorine are 212 and 380 nsec, respectively, in disagreement with the experimental values of 172 ± 12 nsec (argon) and 280 ± 25 nsec (chlorine). Due to the long lifetimes and consequent long decay flight paths, these last two lifetimes were derived from measurements taken over less than a half-life of the decaying state. Beam-foil lifetime measurements have heretofore been generally restricted to shorter lifetimes and flight paths, and the question must arise whether it is possible to perform a meaningful lifetime measurement when working with such long flight paths and such a small fraction of a decay length. We have considered it important therefore to attempt to measure the lifetime of a system whose theoretical lifetime is accurately known, but which is in the hundreds-of-nanosecond range.

We have chosen for test cases the $2E1$ spontaneous decay of $2s_{1/2}$ state in hydrogenlike oxygen and fluorine. The theory of this decay must be regarded as being on very firm ground. It assumes only the Hamiltonian for electric dipole decay applied in second-order perturbation theory to the hydrogenic system. Detailed calculations of the lifetime of this state in a nonrelativistic approximation have been performed by many workers,[2] all of whom confirm that

$$\tau(2s_{1/2}) = (1/8.226)Z^{-6} \text{ sec} . \quad (1)$$

It has further been shown that relativistic corrections and contributions from $M1$ decay are less than 5% up to $Z = 20$.[3] Measurement of the lifetime of this state has been previously made in argon ($Z = 18$), sulphur ($Z = 16$),[4] and He^+ ($Z = 2$),[5] where excellent agreement with the predictions of Eq. (1) was found. This experimental confirmation of Eq. (1) at low Z and high Z thus gives us confidence that we can rely on the theoretical lifetimes for the $2s_{1/2}$ state for intermediate Z. For oxygen and fluorine, these lifetimes are 228 and 464 nsec, respectively, suitably long to present good test cases. This paper reports the beam-foil measurement of these two lifetimes.

EXPERIMENT

The $2s_{1/2}$ state in oxygen and fluorine was produced by foil-exciting 15–35-MeV beams of these elements from the Kansas State University Tandem van de Graaff accelerator. Rather than attempt to detect low-energy photons from the free $2E1$ decay of the $2s_{1/2}$ state directly, we have measured the $2s_{1/2}$ component of the excited beam by Stark-mixing the $2s_{1/2}$ and $2p_{1/2}$ states within view of a thin-window proportional counter. As shown in Fig. 1, the excited beam passes between the pole pieces of a small electromagnet which provides a field of approximately 1.8 kG at a pole separation of 1 cm. The moving ion experiences a motional electric field in its rest frame of strength sufficient to quench roughly 1 (20 MeV fluorine) to 3 (30 MeV oxygen) % of the $2s_{1/2}$ states, giving rise to monoenergetic photons of 826 eV for fluorine, and 652 eV for oxygen, which are detected by the proportional counter. Sample

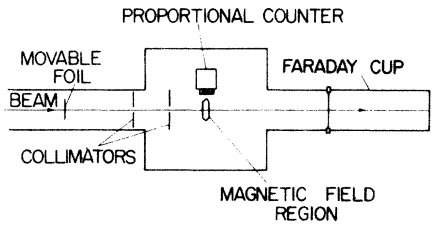

FIG. 1. Schematic diagram of apparatus.

spectra from the proportional counter are shown in Fig. 2 with the current in the electromagnet on and off. The field-off spectrum was subtracted from the field-on spectrum and the number of remaining counts, normalized to the charge collected in the Faraday cup, was taken as a measure of the fraction $2s_{1/2}$ states which survive the flight between exciting foil and detector assembly.

Figure 3 shows the resulting count as a function of foil-dector separation for fluorine beams of 20 and 35 MeV and oxygen beams of 15 and 30 MeV. The decrease in counts with increasing separation is presumed to be due to decay in flight of the $2s_{1/2}$ states via $2E1$ emission. All curves display a slight convex curvature over early portions of the decay curve. This curvature may result from feeding of the $2s_{1/2}$ state by moderately long-lived cascades with lifetimes shorter than that of the $2s_{1/2}$ state. Lack of quantitative information on

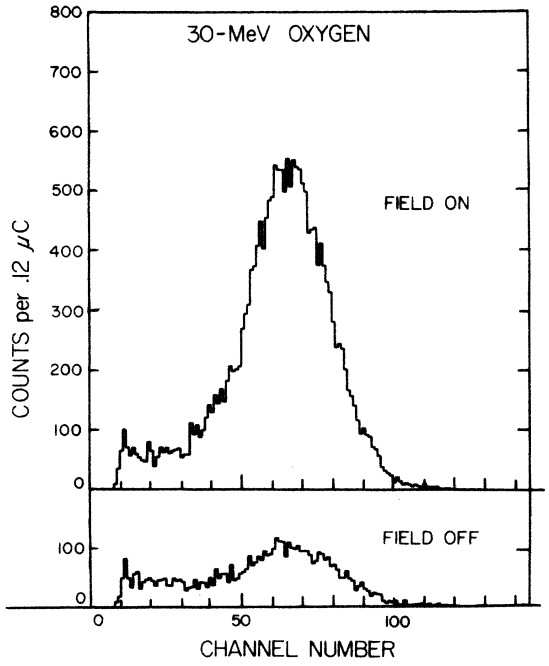

FIG. 2. Proportional counter spectra with magnetic field on and off.

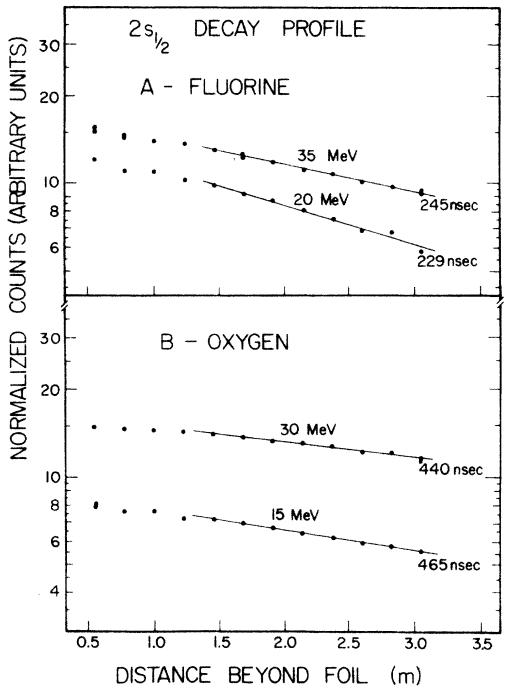

FIG. 3. $2s_{1/2}$ decay profiles.

the population of high-n states in the fluorine and oxygen systems precludes our making a more quantitative analysis of this phenomenon. However, we point out that significant cascading far from the exciting foil has previously been seen in foil-excited fluorine beams.[6] We note that cascading can only make the measured lifetime larger than the theoretical lifetime.

We have fit our curves to single exponentials for distances greater than 1.3 m in order to minimize effects of such cascading. We display the lifetime results in Table I, and the resulting fits in Fig. 3. For comparison, we also show in Table I the results of fitting each entire decay curve to a single exponential. The latter process produces systematically longer lifetimes than does the former, but gives poorer fits to the data.

TABLE I. Experimental $2s_{1/2}$ lifetimes.

Ion	Energy (MeV)	τ (ns) [a]	τ, all points (ns)
F IX	35	245	262
	20	229	251
O VIII	30	440	528
	15	465	535

[a] Fit to points for foil-detector separation greater than 1.3 m.

RESULTS

The average lifetimes found for the $2s_{1/2}$ states in fluorine and oxygen are respectively, 237 ± 17 and 453 ± 43 nsec, where the quoted error bars are estimated from the range of lifetimes obtained from fitting points over different parts of the decay path and data from different beam energies. These lifetimes are in good agreement with the theoretical lifetimes of 228 nsec (fluorine) and 464 nsec (oxygen). We conclude that it is indeed possible to obtain accurate beam-foil lifetimes from measurements on small fractions of a decay length for systems living hundreds of nanoseconds. It thus remains difficult to explain the difference between theoretical and experimental lifetimes for the $2\,^3S$ state in heliumlike sulfur and argon as an experimental artifact.

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