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Relativistic Magnetic Dipole Emission: Lifetime of the $1s2s\ ^3S_1$ State of Heliumlike Argon*

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The lifetime of the $1s2s\ ^3S_1$ state of the heliumlike atom Ar XVII has been measured by observing the decay in flight of the metastable component of a fast foil-excited beam. The decay occurs predominantly by relativistic magnetic-dipole emission, a process first discussed by Breit and Teller. The result, $\tau(2^3S_1) = (172 \pm 30) \times 10^{-9}$ sec, is compared with a recent calculation by Drake of the $M1$ transition probability.

Until recently it was believed that the primary decay mode for the $1s2s\ ^3S_1$ state of two-electron atoms would be spin-orbit–induced double electric-dipole ($2E1$) emission. This process was first suggested by Breit and Teller,[1] and has been accurately calculated by Drake, Victor, and Dalgarno[2] and Bely and Faucher.[3] However, in 1969 Gabriel and Jordan[4] reported the observation of solar coronal lines corresponding to the $1s2s\ ^3S_1$-$1s^2\ ^1S_0$ energy separation for the helium isoelectronic sequence C V-Mg XI, and the Fe XXV line has been reported by Neupert and Swartz,[5] indicating that the primary decay mode is single-photon emission. Single-photon emission also was discussed by Breit and Teller,[1] who pointed out that relativistic effects can lead to magnetic-dipole radiation (this is identically zero in the nonrelativistic approximation). More recently Schwartz[6] and Drake[7] have studied this process and conclude that, to relative accuracy Z^{-1}, the dominant contributions come from kinetic-energy and finite-wavelength corrections to the magnetic-dipole moment, which have nonzero matrix elements between the 1^1S_0 and 2^3S_1 states. Schwartz[6] has calculated the rate of this process using hydrogenic wave functions and energies. He obtains the asymptotic (to large Z) result $A_{M1}(2^3S_1 - 1^1S_0) = 1.66 \times 10^{-6} Z^{10}\ \text{sec}^{-1}$, which yields, for argon ($Z = 18$), $\tau_{M1}(2^3S_1) = 169$ nsec. More accurate calculations have been performed by Drake[7] using correlated wave functions and energies, with the result for argon $\tau_{M1}(2^3S_1) = 194$ nsec.

The astrophysical importance of the lifetime of the 2^3S_1 state has recently been emphasized by Gabriel and Jordan.[8] These authors have developed a theory for deducing the electron density in the solar corona based on intensity measurements. A crucial parameter in this theory is the 2^3S_1 lifetime and they have derived a semiempirical value[9] of $\tau_{M1}(2^3S_1) = 2.3 \times 10^{-10} \lambda^5$ sec (λ in Å) which yields for argon a value of 230 nsec. The 2^3S_1-1^1S_0 transition in the heliumlike ions Si XIII, S XV, and Ar XVII has been observed in the laboratory by Marrus and Schmieder[10] with the beam-foil method, thus confirming the single-photon decay mode, but as yet no experimental lifetime of any $1s2s\ ^3S_1$ state has been reported. In this Letter we report the measurement of the lifetime of the $1s2s\ ^3S_1$ state of Ar XVII, using the beam-foil method. The result is

$$\tau(2^3S_1) = 172 \pm 30 \text{ nsec}.$$

The apparatus used in this measurement is illustrated in Fig. 1. Argon-40 ions in the +14 charge state having an energy of 10.3 MeV/nucleon ($\beta = 0.148$) are obtained from the Berkeley heavy-ion linear accelerator (HILAC) and are

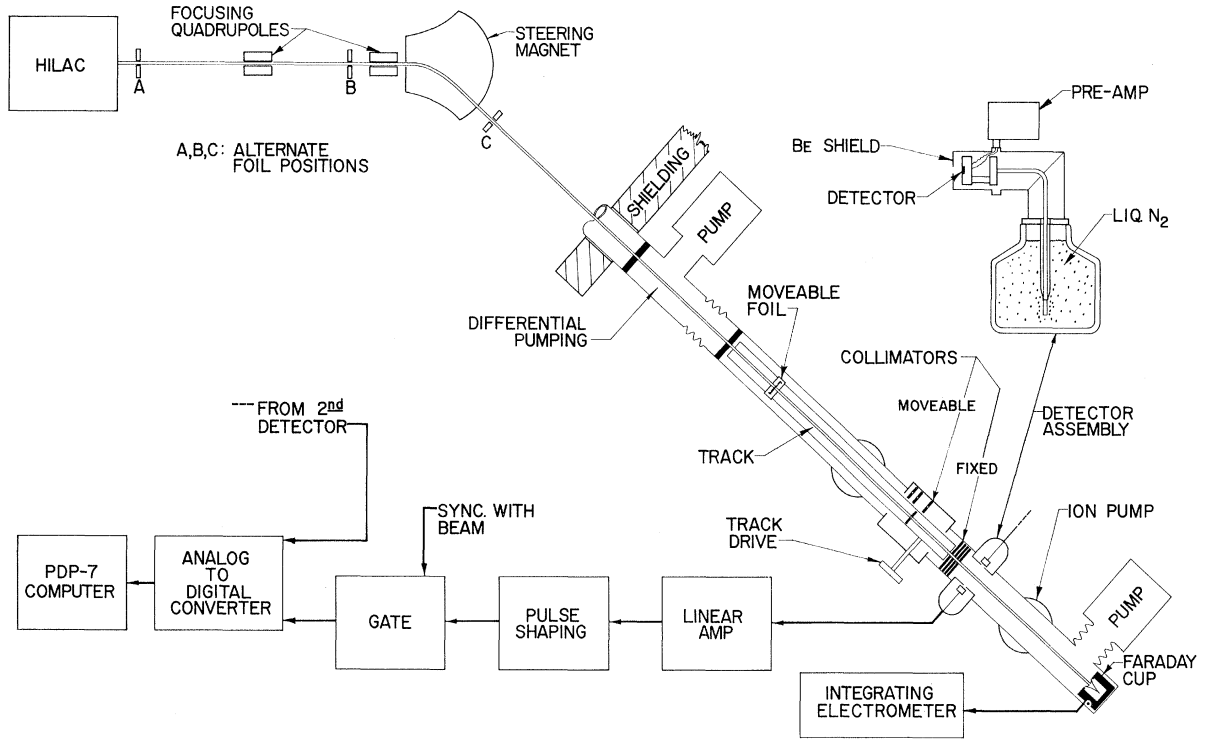

FIG. 1. Schematic diagram of the apparatus.

magnetically deflected into the high-vacuum region, where the pressure is a few microtorrs. The beam is passed through a 100-μg/cm^2 Be foil mounted on a movable track, emerging with the approximate charge distribution +16 (25%), +17 (50%), +18 (25%). Some of the ions emerging with +16 or +17 charge will be excited, and will quickly de-excite to the 1S ground states or the 2S metastable states. Ions in the $1s\ ^2S_{1/2}$ (hydrogenlike) and $1s2s\ ^1S_0$ (heliumlike) states decay to their ground states with $1/e$ decay lengths of a few centimeters (for our beam velocity $v = 0.148c$), and at distances over 75 cm, only the $1s2s\ ^3S_1$-$1s^2\ ^1S_0$ decay (with $1/e$ length $\cong$750 cm) is appreciably present. The photons ($E \cong 3.1$ keV) emitted in flight are detected with a windowless Si(Li) x-ray detector of the type normally used for nuclear gamma spectroscopy. The resolution of this device (cooled to 77°K) is about 200 eV at 3 keV, but we purposefully permitted a large Doppler broadening so that the detector would have a large angular field of view. The broadening is of no consequence to this measurement since only the total number of counts within the peak was used in determining the lifetime.

Pulse shaping and timing is performed with conventional electronics, and pulse-height analysis is performed with an analog-to-digital converter and a PDP-7 computer. Signal (number of counts within full width at 0.1-maximum of peak) was normally 50 to 100 times background (number of counts within equal width, away from peak). A typical spectrum is shown in Fig. 2; further information on the identification of this line is given in Ref. 10.

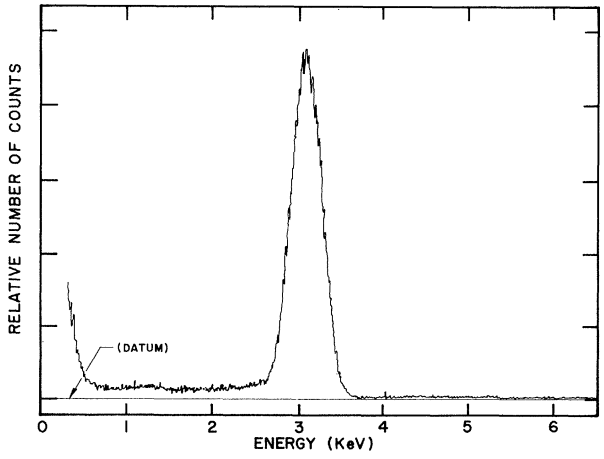

FIG. 2. Typical spectrum obtained with the foil at 190 cm. The peak at 3.10 keV is the 2^3S_1-1^1S_0 M1 line; the rise below 500 eV is noise of electronic origin. The line is Doppler-broadened to about twice the detector resolution.

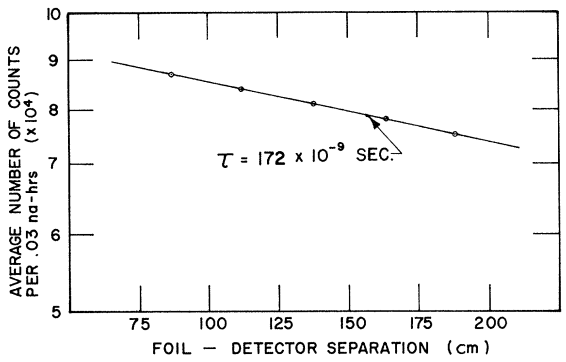

FIG. 3. Typical decay curve (semilog scale). The line represents the mean lifetime determined by least squares from several such plots, obtained independently. The statistical error on each point is roughly the size of the points.

The lifetime was determined by plotting the counting rate (peak minus background) for several foil-detector distances between 75 and 200 cm. The rates were normalized to a total charge of beam passing the detector (0.030 nA h), as measured by an integrating electrometer driven by the Faraday cup which stops the beam. In order to compensate for slow variations in the beam and/or apparatus, the data were accumulated in short time intervals (~3 min), moving the foil cyclically through five or six positions. Successive counts for each position were then averaged. Also two independent detectors (facing each other) were used, and the results averaged. In each of six independent runs, about 10^5 photons were recorded for each foil-detector distance.

A typical decay curve obtained in this way is shown in Fig. 3. Although the total decay is small, the counting rate appears to decay exponentially. The lifetime was computed by performing a least-squares fit of the data with the function ae^{-bx} determining b, and thus $\tau = 1/bv$. The final result, $\tau(2^3S_1) = (172 \pm 30) \times 10^{-9}$ sec, was obtained as a weighted average of the results of the independent runs. The error quoted here is 2 times the mean error, or roughly 95% confidence. The main contributions to the mean error are believed to be due to slow drifts in beam and/or foil properties, and other systematic errors such as foil tracking, beam current integration, and detector efficiency (nominally 80%). The beam velocity, necessary for converting the mean decay length to a mean lifetime, is known from time-of-flight measurements to within 2%. Correction for velocity degradation by the foil has been made. Background corrections were typically 1%.

In order to test the pressure dependence of the measurements, the pressure was increased by a factor of 2.5. No significant deviations in the counting rates were observed, implying that collisions quenching between the foil and detector (typically ~10^{13} residual gas atoms per cm^2) is negligible. We have also shown that these results are independent of foil material (a 15-μg/cm^2 C foil and a 600-μg/cm^2 Ni foil were also used), beam current, counting rate, detector operation, etc.

The chief uncertainty in the interpretation of the data in Fig. 3 is whether the decay is truly exponential. Although this difficulty is unresolvable at the present time, reasonable arguments can be made that "feeding" of the 2^3S_1 state from higher states should be quite negligible beyond 100 cm ($\tau \sim 25$ nsec). Furthermore, we have observed decays of other long-lived states ($2^2S_{1/2}$, 2^3P_2) which are exponential over many mean lives. It is unlikely that Fig. 3 represents any decay but the pure 2^3S_1 state.

We are grateful to A. Ghiorso for his encouragement of this work, to F. Goulding and J. Walton for assistance with the detectors, to F. Grobelch for providing the foils, to R. Diamond and F. Stephens for use of the computer, to D. MacDonald for engineering in all phases of the apparatus, to W. Harnden and W. Davis for assistance in taking the data, and to the operating staff of the Berkeley HILAC throughout these measurements. G. W. F. Drake kindly sent a preprint of his calculations prior to publication.

Note added in proof. —Since this Letter was written, both Drake and Schwartz have extended their calculations of A_{M1}. For Ar XVII, Drake obtains $A_{M1} = 4.709 \times 10^6$ sec^{-1} ($\tau = 212.7$ nsec), while Schwartz obtains $A_{M1} = 4.80 \times 10^6$ sec^{-1} ($\tau = 208$ nsec), the main difference in these values being due to the use of different wave functions. Thus, it appears that a significant discrepancy exists between the calculated and measured lifetimes of the 2^3S_1 state.

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He_3^+ and He_4^+ in 300°K Helium Plasmas: Their Effect on Recombination Loss of Electrons*

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The work reported here establishes the existence of He_3^+ and He_4^+ at room temperature (300°K) in a helium afterglow. The data presented in this paper indicate that the often-measured electron-ion recombination coefficient in 300°K helium afterglows is mainly attributable to electron recombination with He_3^+ rather than, as is usually assumed, with the dominant ion He_2^+.

The electron-ion recombination coefficient in 300°K helium plasmas has been widely studied for the past 20 years by several different groups.[1-6] The measured recombination rate has usually been assigned to He_2^+ if the gas pressure is greater than a few Torr. Results are presented in this paper which indicate that at room temperature and pressures greater than a few Torr, the measured recombination rate can be attributed to electron recombination with He_3^+ even though it is a minority ion.

In 1968, Patterson[7] reported measurements of an ion observed in helium at gas temperatures below 200°K. He concluded that this ion was the triatomic helium ion He_3^+. A mass-12 ion, assumed to be He_3^+, was seen in a flowing afterglow.[8] Isotope measurements have confirmed that He_3^+ and He_4^+ exist in a helium afterglow at a temperature of about 80°K.[9] There have been several other mass-spectrometric observations of mass 12 in helium plasmas[10,11] where the authors have postulated that the observed ion was He_3^+. Unfortunately, in those experiments the presence of other impurities as well as the relative abundance of the mass-12 ion makes it more likely that the observations pertained to C^+.

The work reported here establishes the existence of He_3^+ and He_4^+ at room temperature (300°K) in a helium afterglow. The equilibrium concentration ratios of these ions have also been determined.

He_3^+ and He_4^+ have atomic mass units of 12 and 16, respectively. As is well known, C^+ and O^+ have the same respective masses. Consequently, in order to avoid misinterpretation of the data the isotope of helium ^3He was used in this study. Figure 1(a) shows a time-integrated mass spectrum taken at 15 Torr. Mass 7 ($^{4,3}He_2^+$) is due to a trace of ^4He. The ions observed are He_2^+ and two ions at masses 9 and 12. In order to establish the identity of the latter masses, ^4He was added. The resulting expanded mass scan is shown in Fig. 1(b). Masses 9, 10, 11, and part of 12 are He_3^+ while the remainder of mass 12, and masses 13 and 14 are He_4^+. The superscripts on the chemical terms in Fig. 1(b) indicate the mass structure of the molecular ion. The absence of O^+ (mass 16) indicates that the mass-12 peak is not due to C^+. A quadrupole mass filter which employed a Bendix Channeltron as an ion detector was used to obtain these mass

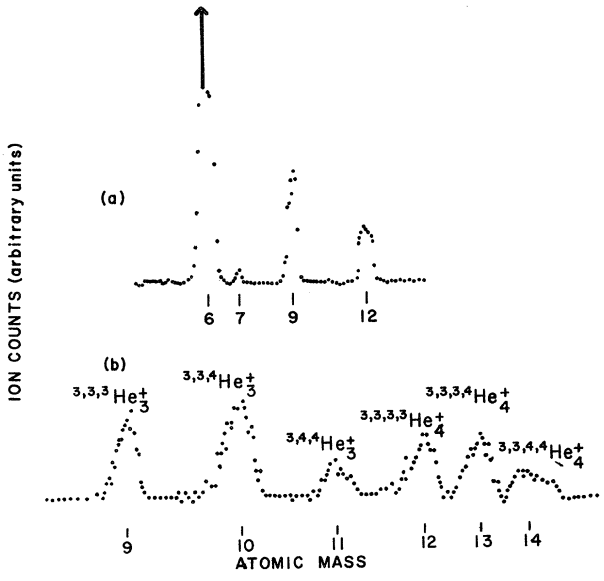

FIG. 1. (a) Time-integrated mass spectra of ^3He afterglow. (b) Time-integrated mass spectra of ^3He and ^4He afterglow. (b) was taken at a different scan speed than (a).