†Work performed under the auspices of the U. S. Atomic Energy Commission.

*Partly supported by a fellowship from the John S. Guggenheim Foundation.

‡Present address: Sandia Laboratories, Livermore, Calif.

[1]G. Breit and E. Teller, Astrophys. J. 91, 215 (1940).

[2]G. Feinberg and J. Sucher, Phys. Rev. Lett. 26, 681 (1971); G. W. F. Drake, Phys. Rev. A 5, 1979 (1972); H. R. Griem, Astrophys. J. 156, 1103 (1969); I. L. Beigman and V. I. Safronova, Zh. Eksp. Teor. Phys. 60, 2045 (1971) [Sov. Phys. JETP 33, 1102 (1971)].

[3]G. W. F. Drake, Phys. Rev. A 3, 908 (1971).

[4]A. H. Gabriel and C. Jordan, Nature (London) 221, 947 (1969), and Mon. Not. Roy. Astron. Soc. 145, 241 (1969).

[5]R. Marrus and R. W. Schmieder, Phys. Lett. 32A, 431 (1970).

[6]H. W. Moos and J. R. Woodworth, Phys. Rev. Lett. 30, 775 (1973).

[7]R. Marrus and R. W. Schmieder, Phys. Rev. A 5, 1160 (1972).

Decay of the 2^3S_1 State in Heliumlike Chlorine*

C. L. Cocke, B. Curnutte, and R. Randall

Department of Physics, Kansas State University, Manhattan, Kansas 66506

(Received 2 July 1973)

The lifetime of a long-lived K x-ray emitter produced in foil excitation of chlorine beams between 40.3 and 57.5 MeV has been measured to be 280 ± 25 nsec. The measured photon energy of the transition indicates that it arises from the $1^1S_0 \leftarrow 2^3S_1$ decay in heliumlike chlorine. The observed lifetime is shorter than the theoretical $M1$ lifetime of 381 nsec predicted for this transition.

The slow decay of the 2^3S_1 state in heliumlike systems has long been of interest both to atomic theorists and to astrophysicists. The major decay is now thought to be the relativistically induced magnetic dipole emission to the 1^1S_0 state, competition from a two-photon decay to the same final state being negligible by comparison for all Z. Photons corresponding to this decay were identified in the solar-coronal spectrum by Gabriel and Jordan[1] for several heliumlike ions with Z between 6 and 12 and their intensities relative to those corresponding to the $1^1S_0 - 2^1P_1$ and $1^1S_0 - 2^3P_1$ decays were used to derive coronal electron densities.[2] Largely stimulated by these identifications several authors have now made calculations of the $M1$ rate.[3-6] Direct experimental verification of these calculations has been difficult because the transition is quite weak. The predicted lifetime of the emitting state scales approximately as Z^{-10} and ranges from 7861 sec in He I to 5 nsec in Fe XXV.[4] Schmieder and Marrus[7] have previously reported a beam-foil lifetime of the 2^3S_1 state in Ar XVII to be 172 ± 30 nsec, slightly shorter than the 212 nsec calculated by Drake.[4] This result is confirmed and a similar measurement in Ti XXI is reported in the preceding paper.[8] Moos and Woodworth[9] find a transition rate near 2.5×10^{-4} sec^{-1} in He I, larger than the theoretical rate of 1.27×10^{-4} sec^{-1}, but assign an experimental uncertainty of a factor of 3 to their result. It is the purpose of this paper to report a beam-foil measurement of the lifetime of this state in Cl XVI. The experimental lifetime is again found to be shorter than the theoretical one.

We remark at the outset that in both Ar XVII and Cl XVI the predicted lifetimes are sufficiently long (212 and 381 nsec, respectively) that measurements over very long flight paths are necessary. Because of the Z^{10} scaling of the $M1$ rate, measurements at higher Z should be considerably easier. One is thus entitled to suspect that any discrepancy between theory and experiment which increases as one lowers Z below about 20 might be due as much to experimental as to theoretical problems. Close attention to the experimental approach is thus important, and ours is described in some detail below. In spite of this experimental difficulty we nevertheless feel that the importance of the direct measurement makes it important that one press the beam-foil experiment to as low Z as possible.

We have foil-excited chlorine beams of 40.3 to 57.5 MeV (incident charge states +6 to +9) from the Kansas State University tandem Van de Graaff accelerator and have traced the decay curve of chlorine K x rays from the beam over a flight path extending 2.7 m beyond the foil. Angular collimation of the beam was achieved by 3- and 5-mm collimators separated by a distance of 5.7 m as shown in Fig. 1. The smaller aperture was

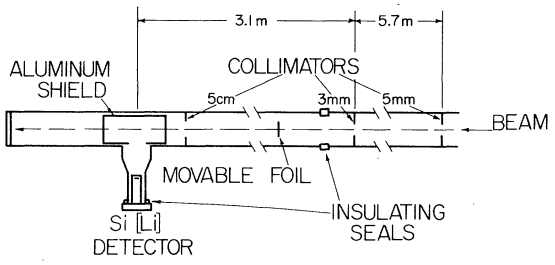

FIG. 1. Schematic diagram of apparatus.

located 20 cm before entrance to that section of the beam tube downstream of the larger insulating seal in Fig. 1, hereafter referred to as the flight tube. The exciter was typically a 40-μg/cm^2 carbon foil 1.27 cm in diameter which was carefully aligned so that it intercepted all beams passing the collimation system at all foil positions. Variation of the flight path was achieved by changing the foil location.

The x rays were detected by a Si[Li] detector (1 cm^2 area; 200 eV resolution at 5.9 keV) which viewed the beam at right angles in one of two different geometries. For that shown in Fig. 1 an aluminum shield allowed the detector to view a 5 cm length of beam 5 cm high with no further collimation on the detector itself. The second geometry used a cylindrical graphite collimator, 1.5 cm in diameter and 3 cm long, with an open aluminum shield. Detector-beam distances of 11 and 17 cm were used with each geometry. A 5-cm-diam collimator, located 20 cm before the region viewed by the Si[Li] detector, prevented chlorine ions scattered through wide angles in the foil from striking the walls of the tube within view of the Si[Li] detector. The aluminum lining of the detector region allows us to monitor this source of background since the aluminum K x rays are produced slightly more readily than are Cl K x rays in Cl-Al collisions and are distinguishable in the Si[Li] detector spectrum. The beam charge was measured on the entire flight tube. The measured beam current was found to be independent of foil position for foil-detector distances less than 2.7 m.

A typical decay curve is shown in Fig. 2(a). A direct scan of the vertical beam profile was made at two foil positions by scanning a slit, 3 mm high by 5 cm long, vertically across the opening in the aluminum shield. The profile, shown in Fig. 2(b), shows that the beam was well within the region over which the detector-beam collimation system allowed a constant detection efficiency.

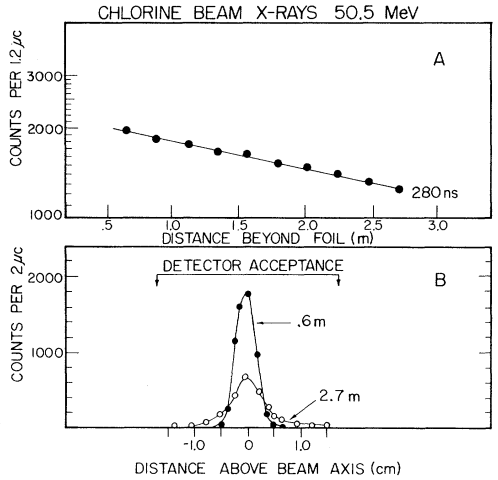

FIG. 2. (a) Sample decay curve. (b) Vertical profile of the x-ray–emitting component of the beam at two foil-detector distances. The exciter was a 40-μg/cm^2 carbon foil. "Detector acceptance" indicates that region over which the detector-beam collimation system allowed a constant detector efficiency.

The following variations were made in the experimental arrangement with no detectable effect on the lifetime: (1) Beam energies of 40.3, 50.8, 51.5, and 57.5 MeV were used. Background, defined as the counting rate with no foil, was as high as 10% at 40.3 MeV, negligible at the higher energies. The increasing importance of this background prevented us from working with lower bombarding energies. (2) Two detector geometries at two detector-beam distances each were used. (3) The pressure was raised an order of magnitude by introducing a controlled leak in the detector region. (4) Foils of 20 and 40 μg/cm^2 were used. (5) The diameter of the "5-mm" upstream collimator was varied between 3 and 7 mm. The weighted average of eleven lifetime measurements was found to be 280 ± 25 nsec.

The Si[Li] detector resolution was insufficient to allow us to distinguish between x rays from the 2^3S_1 state and those from the $2P$ states. A measurement of the energy of the photon responsible for the long-lived component was therefore made using a Doppler-shift-tuned absorption spectrometer similar to that described by Schmieder and Marrus.[10] Relativistic calculations by Doyle,[11] corrected for electrostatic terms neglected in that paper using the results of Scherr and Knight,[12] predict a photon energy of 2757 eV for the $1^1S_0 \leftarrow 2^3S_1$ transition in Cl XVI. A photon of this energy emitted at 65° to the beam direction by a 50.5-MeV chlorine ion will undergo a Doppler shift

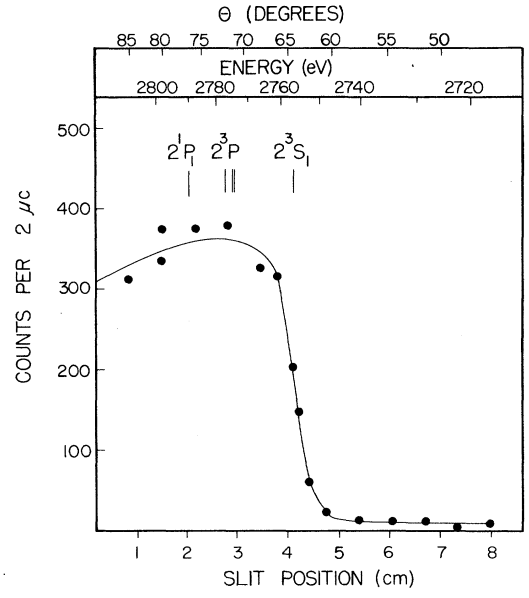

FIG. 3. Yield of chlorine K x rays in the Si[Li] detector versus slit position. The corresponding angle between beam axis and photon emission is shown at the top of the figure. The detector was covered by a 50-μm vinylidene-chloride absorber and viewed the 50.8-MeV beam near 70 cm downstream of the foil. The energy scale shows the energy needed in the rest frame of the chlorine ion in order that the emitted photon undergo a Doppler shift to match the chlorine K absorption edge in the lab system.

such that its lab energy will coincide approximately with the K absorption edge of chlorine. By inserting a thin chlorine-bearing absorber between the Si[Li] detector and the beam, one can thus use a scan of the angle of view to obtain an integral of the photon energy spectrum near the chlorine K edge. Figure 3 shows such a spectrum obtained at 50.8 MeV by scanning a 3-mm-wide vertical slit upstream while the Si[Li] detector, 8 cm from the beam axis and covered by a 50-μm vinylidene-chloride absorber, pointed near 65° to the beam. The average foil detector distance over the scan was 70 cm. The energy scale shown above the figure displays the energy with which the photon must be emitted in the rest frame of the chlorine ion in order to be observed at that angle with the energy of the chlorine K edge, taken to be 2824 eV.[13] (Although we do not know the exact energy of the K edge in our absorber material, this value has yielded good agreement between observed and calculated energies of the $1^1S_0 - 2^3P_2$ transition in similar experiments.) It is seen that the critical absorption occurs at the angle expected for the 2^3S_1 decay. Theoretical energies for $1^1S_0 - 2P$ transitions are indicated on the figure. Evidence for decay through these states is not seen.

Our lifetime 280 ± 25 nsec for the 2^3S_1 state in Cl XVI is shorter than the value of 381 nsec calculated by Drake for the $M1$ radiation channel. In the preceding paper Gould, Marrus, and Schmieder[8] have confirmed the earlier result in argon, finding 172 ± 12 nsec as opposed to the theoretical value of 212 nsec. They also report a value in titanium ($Z = 22$) which is much closer to the theoretical value. The discrepancy between theory and experiment thus appears to increase with decreasing Z. It is unfortunate that the discrepancy becomes evident in just that region of Z where the experiments do not clearly establish the exponential character of the decay curve. We point out, however, that cascading through the 2^3S_1 state would result in an apparent lifetime longer than the true one, while "background" cascading through the $2P$ states is not in evidence in the spectrum of Fig. 3.

The apparent reliability of the theoretical $M1$ rate and the Z dependence of the discrepancy between experiment and theory suggest that one seek a competing mechanism for depleting the 2^3S_1 state. For example, a competing decay mode whose rate varies with Z more slowly than the Z^{10} $M1$ scaling is suggested by the data. Whether such a mechanism is inherent in the isolated heliumlike system or is some yet unidentified characteristic of foil-excited systems is an important question still deserving investigation.

We thank R. Marrus for communication of experimental results prior to publication and C. P. Bhalla for illuminating discussions.

*Work supported in part by the U. S. Office of Naval Research and by the U. S. Atomic Energy Commission.

[1]A. H. Gabriel and C. Jordan, Nature (London) 221, 947 (1969).

[2]A. H. Gabriel and C. Jordan, Mon. Notic. Roy. Astron. Soc. 145, 241 (1969); A. H. Gabriel and C. Jordan, Phys. Lett. 32A, 166 (1970); F. F. Freeman, A. H. Gabriel, B. B. Jones, and C. Jordan, Phil. Trans. Roy. Soc. London 270, 127 (1971).

[3]H. R. Griem, Astrophys. J. Lett. 156, L103 (1969), and 161, L155 (1970).

[4]G. W. F. Drake, Phys. Rev. A 3, 908 (1971).

[5]G. Feinberg and J. Sucher, Phys. Rev. Lett. 26, 681 (1971).

[6]C. Schwartz, private communication cited in Ref. 4.

[7]R. W. Schmieder and R. Marrus, Phys. Rev. Lett. 25, 1245 (1970); R. Marrus and R. W. Schmieder, Phys. Rev. A 5, 1160 (1972).

[8]H. Gould, R. Marrus, and R. W. Schmieder, preceding Letter [Phys. Rev. Lett. 34, 504 (1973)].
[9]H. W. Moos and J. R. Woodworth, Phys. Rev. Lett. 30, 775 (1973).
[10]R. W. Schmieder and R. Marrus, Nucl. Instrum. Methods 110, 459 (1973).
[11]H. T. Doyle, in *Advances in Atomic and Molecular Physics*, edited by D. R. Bates (Academic, New York, 1969), Vol. 5, p. 337.
[12]R. E. Knight and C. W. Scherr, Rev. Mod. Phys. 35, 431 (1963).
[13]C. Sugiura, J. Chem. Phys. 58, 3527 (1973).

Inelastic Neutron Scattering from a Liquid ^{3}He-^{4}He Mixture*

J. M. Rowe
Solid State Science Division, Argonne National Laboratory, Argonne, Illinois 60439, and Institute for Materials Research, National Bureau of Standards, Washington, D. C. 20234

and

D. L. Price and G. E. Ostrowski
Solid State Science Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 18 June 1973)

We report inelastic-neutron-scattering measurements on liquid $^3He_{0.05}{}^4He_{0.95}$ in the Q region from 0.8 to 2.3 Å^{-1} at 1.6 K. The shifts and increases in natural linewidth of the single excitation peaks relative to pure ^{4}He at the same temperature were determined by a least-squares fitting procedure. The shifts vary from a small, possibly negative, value at the roton minimum to positive values around 0.5 K at both ends of the Q range. The full widths at half-maximum of the extra broadening vary from 0.5 to 1.5 K over the same range.

Inelastic-neutron-scattering measurements on liquid ^{4}He demonstrated as early as 1958 the unique nature of the elementary excitations in that quantum liquid.[1] Neutron measurements on liquid ^{3}He and ^{3}He-^{4}He mixtures, however, have been discouraged by the large ratio of absorption to scattering cross section for ^{3}He nuclei (about 5000:1 at thermal energies). Information about the elementary excitations in these liquids has therefore been obtained indirectly. The most direct measurements reported so far on ^{3}He-^{4}He mixtures have been those recently made of zero-momentum roton pairs by Raman scattering.[2] The information obtained, however, is limited to the roton minimum and can be influenced by interactions between the rotons making up the pair. Fortunately improvements in the reliability and accuracy of the neutron method made in the last few years, together with the recent adoption of correlation techniques,[3] now make it possible to measure highly absorbing systems such as ^{3}He and its solutions. As the first part of a program to study the excitations in these fluids, we present here results for a 5% solution of ^{3}He in ^{4}He at 1.6 K. At this temperature the ^{3}He atoms form essentially a classical system, but the influence of this system on the ^{4}He excitations nevertheless provides unique information on the nature of the ^{3}He-^{4}He interaction.

The measurements were made on the thermal-neutron time-of-flight system[4] at the CP-5 Reactor at Argonne, with a 4.05-Å beam produced by reflection from pyrographite monochromators and the correlation chopper described by Sköld.[3] Data were collected in fifteen independent groups of three detectors each. The mean scattering angles ranged from 30° to 108° to cover a Q range of 0.8 to 2.5 Å^{-1} (for elastic scattering). The angles subtended by the groups of detectors at the sample ranged from 1.8° to 3.0°, depending on the spacing. The channel width for the time-of-flight analysis was 20 μsec so that 251 time channels (the number of elements in the pseudorandom sequence) equaled the rotor period of 5020 μsec. Runs were made on the empty container (44 h), liquid ^{4}He as a baseline reference (135 h), and the $^3He_{0.05}{}^4He_{0.95}$ mixture (636 h). The samples were contained in a holder consisting of a parallel array of Al-alloy capillary tubes, 0.55-mm internal diameter, similar to that used in an earlier measurement on liquid argon.[5] The volume of sample seen by the neutron beam was 1.45 cm^3. The holder was attached to the tail-piece of a standard helium cryostat in which the